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TECHNICAL NOTE

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REACTOR-WEIGHT STUDY OF BERYLLIUM OXIDE, BERYLLIUM, LITHIUM-7 HYDRIDE, AND WATER AS MODERATORS WITH TUNGSTEN 184 STRUCTURAL MATERIAL AND URANIUM DIOXIDE FUEL

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REACTOR-WEIGHT STUDY OF BERYLLIUM OXIDE, BERYLLIUM, LITHIUM-7 HYDRIDE, AND WATER AS MODERATORS WITH TUNGSTEN 184 STRUCTURAL MATERIAL AND URANIUM DIOXIDE FUEL

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SUMMARY

A series of criticality calculations using consistent P1 equations governing the neutron slowing-down process establishes minimum weights for bare, homogeneous, thermal reactors. The reactors employ enriched uranium dioxide as the fuel, tungsten enriched with isotope 184 as the fuel-bearing and structural material, and the following moderators: beryllium oxide, beryllium, lithium-7 hydride, and water.

Results for each moderator over a wide range of reactor cross-sectional void area indicate that water and lithium-7 hydride moderated reactors are the lightest with beryllium oxide moderated reactors the heaviest. For a void area of 1 square foot, a volume ratio of uranium dioxide to uranium dioxide plus tungsten of 0.30, and 800 pounds of tungsten 184 per square foot of void area, the following reactor weights were obtained: 4400 pounds with a beryllium oxide moderator, 2600 pounds with a beryllium moderator, and 1100 pounds with either a lithium-7 hydride or a water moderator. The increases in minimum reactor weight per square foot of void area for the above conditions are approximately: 1700 pounds for beryllium oxide moderators, 1400 pounds for beryllium moderators, and 1000 pounds for either lithium-7 hydride or water moderators. Additional results are presented for bare cores using 600 and 1000 pounds of tungsten 184 per square foot of void area.

For reactors moderated with water, variations in the fuel concentration and in the tungsten 184 enrichment indicated that concentrations between 0.15 and 0.20 were most suitable for a range of void area from 0.2 to 4 square feet and that reducing the tungsten 184 enrichment from 100 to 78 percent resulted in reactor weight increases of 10 to 27 percent for void areas ranging from 3.5 to 0.5 square foot, respectively.

INTRODUCTION

Studies to determine the potential of nuclear rockets for space missions require the analysis of many reactor concepts. These studies require parametric data on reactor weight and size over a wide range of conditions to determine the best operating conditions for any particular space mission.

The purpose of this report is to determine minimum reactor weights for various bare, homogeneous, thermal reactors with high-temperature capabilities having possible nuclear application for a range of reactor flow areas up to 10 square feet. If acceptable values of reactor-exit temperature, exit Mach number, exit- and core-pressure drop are used to determine the mass velocity (i.e., the weight flow per unit flow area), reactor power is a function either of reactor flow area or void area; it is used as a function of the latter in this report. The reactor weights are, therefore, shown as functions of the reactor cross-sectional void area.

The present study is restricted to thermal reactors employing beryllium oxide (BeO), beryllium (Be), lithium-7 hydride (Li^7H), and water (H_2O) as moderators with uranium dioxide (UO_2) as the fuel and tungsten (W) enriched with tungsten 184 (W^{184}) as the fuel-bearing and structural material. Tungsten was selected because of its high-temperature capability (m.p. of approx. 3410° C) and its compatibility with hydrogen (H_2) and UO_2. The weights, sizes, and uranium 235 (U^{235}) investments of bare-core reactors were determined as functions of void area for the various moderator materials, and from these data minimum-reactor-weight curves were obtained. The various moderator materials were then compared on the basis of minimum reactor weight for a range of void cross-sectional area.

In addition to void area, the weight of tungsten per square foot of void area in the reactor is a parameter in the study. For the H_2O moderated cores, both the enrichment with W^{184} and the amount of uranium relative to tungsten are also varied. The corresponding effects on minimum reactor weights were determined.

SYMBOLS

A_v reactor cross-sectional void area, sq ft

a inelastic scattering parameter

B_g^2 geometric buckling

$B_m(u)$	material buckling, lethargy dependent
D_c	core diameter, ft
E	neutron energy, ev
$f(u)du$	fraction of source neutrons in lethargy interval du about u
H_c	core height, ft
h	inelastic scattering spectrum
$J(u)$	neutron current, lethargy dependent
K_{eff}	static criticality factor
k	Boltzmann's constant
$P(u)$	anisotropic slowing-down density
Q	isotropic slowing-down density
R	ratio of moderator to fuel atoms
R_c	reactor radius, ft
S	neutron source due to fissions
T	moderator temperature
u	neutron lethargy
V_{UO_2}	volume of uranium dioxide in reactor
$V_{(UO_2+W)}$	volume of uranium dioxide plus tungsten in reactor
W_r	reactor weight, lb
W_W	weight of tungsten, lb
α	void fraction of reactor frontal area
γ	quantity related to mean squared lethargy by $2\xi\gamma = (u - u')^2$
μ_L	cosine of angle between initial and final directions of motion, in laboratory system, of a neutron undergoing elastic scattering collision
μ_0	average cosine, in laboratory coordinates, for elastically scattered neutrons

μ_1 mean product of lethargy increase in collision times angle of scattering

ν average number of neutrons produced per fission

ξ_1 average increase in lethargy per collision

ρ related to product of squared lethargy increase per collision times angle of scattering

Σ_A macroscopic-neutron-absorption cross section, cm

Σ_{ES} macroscopic-neutron-elastic scattering cross section, cm

Σ_F macroscopic-neutron-fission cross section, cm

Σ_{IN} macroscopic-neutron-inelastic-scattering cross section, cm

Σ_T macroscopic-neutron-total cross section, cm

Φ neutron flux

Subscript:

min minimum

Superscript:

' initial value, highest energy or lethargy in group

PROCEDURE AND ANALYSIS

The present study is restricted to thermal reactors in order to obtain reasonable uranium investments. The following materials were considered as moderators: BeO, Be, Li^7H, and H_2O. Tungsten was selected as the fuel-bearing and structural material because of its high-temperature capability (m.p. of approx. 3410° C) and compatibility with UO_2 (ref. 1) and H_2. Because of the large neutron resonance integral for tungsten (approx. 350 barns, calculated from resonance data in ref. 2), the isotopic separation and the use of isotopic mixtures containing principally W^{184} with a low resonance capture integral (ref. 3) are desirable to obtain small thermal reactors. Separation of natural tungsten to produce isotopic mixtures with high percentages of W^{184}, and thus reduce resonance absorption, is feasible (ref. 4). In most of the study, the tungsten is assumed to be 100 percent W^{184}; deviations from this value are indicated by specifying the percent of W^{184} in the mixture.

The weights of tungsten per square foot of cross-sectional void area W_W/A_v selected were 600, 800, and 1000 pounds; this range is based on estimated heat-transfer surface area and tungsten-thickness requirements. Reactor weights with the various moderators are compared at each of the aforementioned values of tungsten content.

Uranium dioxide, 93 percent enriched with U^{235}, was selected as the fuel. For most of the study, $V_{UO_2}/V_{(UO_2+W)}$ was assumed constant at 0.30. Lower values of this parameter were used in the parametric study on H_2O moderated reactors to show the effect on reactor weight and uranium investment.

The reactor void area (i.e., the flow area plus the moderator-cooling area) was varied over a wide range for each moderator material by a change in the reactor void fraction α, which is the ratio of void cross-sectional area to total frontal area of the core. It should be noted that void area is a measure of reactor power or thrust for a given set of values of pressure, temperature, and Mach number flow conditions at the exit of the reactor. For a given mission the initial stage weight, propellant flow rate, and specific impulse define the propellant weight and tankage requirements. Powerplant component weights, which are either direct or indirect functions of reactor size, flow area, and flow conditions, permit allowable determination of payload. Thus reactor void area is a key criterion of reactor weight and is used as the basis for reactor-weight comparisons. The values of void fraction herein range from 0.10 to 0.60; a change in α also produces a change in R, the ratio of moderator to fuel atoms.

The reactor criticality calculations were based on the materials being homogeneously mixed with void, and a spherical geometry with no reflectors was assumed. The program used in the study was written at the NASA Lewis Research Center for an IBM 704 with 8000-core storage. The basic equations for the diffusion analysis are described in the paragraphs that follow; a more detailed description can be found in reference 5.

The microscopic cross sections used in the program were obtained from references 2 and 6 to 9. Equations (1) and (2) represent the basic lethargy-dependent equations of the consistent P1 approximations to the Boltzmann transport equations for slowing-down neutrons:

$$B_m(u)J(u) + \left[\Sigma_A(u) + \Sigma_{IN}(u)\right]\Phi(u) + \frac{dQ(u)}{du}$$

$$= \frac{f(u)}{K_{eff}} \int_0^\infty du'\nu(u')\Sigma_F(u')\Phi(u') + \int du'\Sigma_{IN}(u')\Phi(u')h(u' \rightarrow u) \qquad (1)$$

$$-\frac{1}{3} B_m(u)\Phi(u) + \left[\Sigma_T(u) - \mu_0(\mu)\Sigma_{ES}(u)\right]J(u) + \frac{dP(u)}{du} = 0 \qquad (2)$$

In addition to equations (1) and (2), two coupling equations are needed to supply coupling between $\Phi(u)$ and $Q(u)$ (eq. (3)) and $J(u)$ and $P(u)$ (eq. (4)):

$$\gamma(u) \frac{dQ(u)}{du} + Q(u) = \xi_1(u)\Sigma_{ES}(u)\Phi(u) \qquad (3)$$

$$\rho(u) \frac{dP(u)}{du} + P(u) = \mu_1(u)\Sigma_{ES}(u)J(u) \qquad (4)$$

Some of the terms in equations (3) and (4) are defined by the following: $\xi_1 \equiv \overline{t}$, $2\xi_1\gamma \equiv \overline{t^2}$, $\mu_1 \equiv \overline{t\mu_L(t)}$, and $2\mu_1\rho \equiv \overline{t^2\mu_L(t)}$

where t is set equal to $u - u'$. The problem is defined when the $\Phi(u)$, $Q(u)$, a source function $S(u)$, and an inelastic scattering spectrum $h(u' \rightarrow u)$ are specified.

When the energy spectrum is started (i.e., $u = 0$) above the source spectrum, then $\Phi(0) = 0$ and $Q(0) = 0$. The source spectrum used for the calculations in this report was a U^{235} fission spectrum, given as

$$S(u) = 0.45324\, E\left[\exp\left(-\frac{E}{0.965}\right)\right]\sinh\sqrt{2.29\,E} \qquad (5)$$

where E is the neutron energy in millions of electron volts. If the source function is normalized so that the integral of the source $\int_0^\infty S(u)du$ is equal to 1, the static criticality factor K_{eff} becomes

$$K_{eff} = \int_0^\infty \nu(u)\Sigma_F(u)\Phi(u)du \qquad (6)$$

In this equation $\nu(u)$ is the number of neutrons produced per fission and $\Sigma_F(u)$ the macroscopic neutron fission cross section.

Using the evaporation model discussed in reference 10 results in the spectrum of the inelastically scattered neutrons in terms of energy:

$$h(E' \rightarrow E) \approx \text{const } Ee^{-E/kT} \qquad (7)$$

where $1/kT$ can be represented as $\sqrt{a/E'}$ and a is a parameter varying with mass number.

Equations (1) to (7) and microscopic cross sections tabulated at 473 energies from 10 million electron volts to 0.025 electron volt were used to determine the static criticality factor of 1 by adjusting values of geometric buckling B_g^2.

With the critical geometric buckling known, various lengths were applied for cylindrical reactors, and the diameter was determined from the geometric buckling for cylinders:

$$B_g^2 = \left(\frac{2.405}{R_c}\right)^2 + \left(\frac{\pi}{H_c}\right) \tag{8}$$

The densities for all materials used are given in table I; no void was assumed. For the calculations in which the isotopic W^{184} concentration is varied, the density used was that of natural tungsten listed in the table.

In the aforementioned variation in W^{184} concentration, the values of the isotopic abundances in mixtures were obtained from reference 4, and the abundances used are in table II. Natural tungsten is listed for the purpose of comparison. The mixtures are referred to in this report by the W^{184} concentration expressed as a percentage of the total mixture.

RESULTS AND DISCUSSION

As described in the section PROCEDURE AND ANALYSIS, critical sizes, reactor weights, and uranium investments of bare, homogeneous, thermal reactors were determined for a range of reactor cross-sectional void area. The study considered the following neutron moderators: BeO, Be, Li^7H, and H_2O. The fuel used was UO_2, fully enriched (93 percent) in U^{235}. Because of the basis used for comparing the reactor weights (viz., a prescribed amount of tungsten and fuel per unit void area) the use of bare reactors would give a close approximation to the minimum weights. This is true only when the weight of the moderator is a small portion of the total weight and/or the reflecting material is approximately the same weight per unit volume as the moderator it would replace. Of the moderators selected, therefore, only the weight of the BeO reactor might be reduced a significant amount by the addition of a comparable reflector of lower density such as Be.

For selected values of tungsten and UO_2 content, reactor weights were plotted as functions of void area and minimum-reactor-weight curves obtained. The tungsten content of the reactor per square foot of void area was chosen to be 600, 800, and 1000 pounds. These values are representative of the tungsten content required for reasonable reactor designs. For the comparison of moderators the ratio $V_{UO_2}/V_{(UO_2+W)}$ was held constant at 0.30. This corresponded to UO_2 content in pounds per square foot of void area of 133, 178, and 222, respectively, at the aforementioned values of tungsten content.

Insofar as the volume percentages of the tungsten and uranium are functions of the cross-sectional void area, they will change for various values of α. Therefore, for a decrease in void area the weights of tungsten and uranium decrease in a manner not proportional to volume and result in an increase in moderator- to uranium-atom ratio R. This leads to the result that minimum reactor volume will not coincide with minimum reactor weight for a given α.

In addition to the comparison of moderators on the basis of minimum reactor weight, the effects of W^{184} enrichment and uranium concentration on reactor weight were examined for the H_2O moderated reactors.

Beryllium Oxide

The weights and dimensions of the bare, homogeneous BeO moderated reactors as functions of reactor cross-sectional void area A_V and void fraction α are shown in figure 1. Figures 1(a), (c), and (e) indicate the reactor weight, and figures 1(b), (d), and (f) present the corresponding reactor dimensions, diameter D_c and height H_c.

In figure 1(a) the void fraction was increased from 0.10 to 0.40 to produce the desired range of reactor void area. An increase in void area at constant α increases the reactor diameter (fig. 1(b)), increases the reactor tungsten content for constant W_W/A_V, and thereby increases the uranium content for constant $V_{UO_2}/V_{(UO_2+W)}$. The net effect of this change is a decrease in the height of a critical reactor (fig. 1(b)). This decrease in height is primarily to compensate for the decrease in neutron leakage when the diameter is increased. The net effect is an increase in reactor weight (fig. 1(a)) with an increase in void area.

If each of the constant-α curves in figure 1(a) were extended to lower void areas, a point of minimum reactor weight for constant α would result; such is the case for $\alpha = 0.10$. Minimum reactor weight for any given flow area is of more merit; this quantity is given by the envelope curve (solid line, fig. 1(a)) tangent to the curves of constant α. Thus at any point, or flow area, on the minimum-weight-reactor curve (solid), an α-value can be found that yields a constant-α curve tangent at that point. No other α would yield a lighter reactor at that particular void area.

The minimum-reactor-weight $(W_r)_{min}$ curves become essentially linear at the higher void areas. This is not surprising, since the weights of tungsten and uranium, which constitute the major portion of reactor weight, are both proportional to void area. In figure 1(c) the slope for the $(W_r)_{min}$ curve indicates an average increase in $(W_r)_{min}$, above 2 square feet of void area, of about 1700 pounds per square foot. Furthermore, a comparison of the $(W_r)_{min}$ curves in figures 1(a), (c), and (e) shows an increase in $(W_r)_{min}$ of 25 to 30 percent for an increase in W_W/A_V from 600 to 1000 pounds per square foot for the entire void-area range.

Beryllium Moderated Reactors

The weights and sizes of bare, homogeneous Be moderated reactors are plotted in figure 2 in an identical manner to that for the BeO reactors of figure 1. The curve characteristics for the Be moderated reactors are similar to those shown for BeO, and the same explanations apply. The minimum reactor weights are considerably lighter than for BeO over the void-area range; this is evident in the section Comparison of Moderators on Basis of Minimum Reactor Weight. The void fractions required for a given void area are essentially the same for Be and BeO, as are the reactor heights and diameters. Hence, the sizeable reduction in reactor weights can be attributed directly to the lower material density of Be, rather than to a change in moderator volume. The slope of the $(W_r)_{min}$ curve (fig. 2(c)) shows an increase in $(W_r)_{min}$ of about 1400 pounds per square foot of void area. An increase in W_W/A_V from 600 to 1000 pounds per square foot results in an increase in $(W_r)_{min}$ of 40 to 50 percent, a greater increase than for BeO.

Lithium-7 Hydride Moderated Reactors

The results for the Li^7H moderated reactors, using the same values of W_W/A_V and $V_{UO_2}/V_{(UO_2+W)}$ as before, are shown in figure 3. Since the better moderating characteristics of Li^7H provide smaller reactors, the void fractions must be increased to obtain a given void area. In figures 3(a), (c), and (e) extending the void fraction to 0.60 provided flow areas up to 6 or 8 square feet as compared to 14 or 16 square feet with a void fraction of 0.40 in Be and BeO.

The minimum-weight Li^7H reactors are considerably lighter than the Be reactors over a common void-area range. For a given flow area, the reactor diameter and length are smaller and the void fraction is larger, and thus the moderator volume is much smaller. The density of Li^7H is considerably lower than that of Be, which further reduces the Li^7H reactor weights.

In addition to the Li^7H other hydrides such as zirconium hydride, were considered. Their hydrogen-atom densities were not as high as that of Li^7H and resulted in larger, heavier reactors. Some of the preliminary calculations placed the reactor weights in the range of the Be moderated results.

The slope of the $(W_r)_{min}$ curve in figure 3(c) shows an increase in $(W_r)_{min}$ of about 1000 pounds per square foot of void area at a W_W/A_V of 800 pounds per square foot. An increase in W_W/A_V from 600 to 1000 pounds per square foot results in an increase in $(W_r)_{min}$ of about 55 to 65 percent. A comparison of these increments indicates that the weight of the Li^7H moderator is the smallest portion of the total weight of the reactor.

Water Moderated Reactors

Since the percentages of hydrogen in water and in Li^7H are practically the same and the densities of the two compounds are also similar, the reactor weights for these two materials would be expected to be approximately equal. On this basis, several calculations were made with the same conditions as those used for the Li^7H moderated reactors. The calculations verified the fact that the reactor-weight curves as functions of void area were about the same. In the following section several of these points appear on the Li^7H curves to illustrate this point.

Comparison of Moderators on Minimum-Reactor-Weight Basis

The various moderators, BeO, Be, Li^7H, and H_2O, are compared in figure 4(a) on the basis of the previous minimum-reactor-weight curves for values of W_W/A_V and $V_{UO_2}/V_{(UO_2+W)}$ of 600 pounds per square foot and 0.30, respectively. The long-dashed line indicates extrapolation.

As indicated by figure 4(a) and in previous discussion the results for a given void area are as follows: (1) the BeO moderated reactors are the heaviest; (2) the Be moderated reactors are considerably lighter than BeO moderated reactors because of the lower moderator material density (no appreciable change in moderator volume); (3) the Li^7H and H_2O reactors are much lighter than the Be reactors because of reductions in both moderator volume (small reactors with larger void fractions) and moderator material density.

The rate of change of minimum reactor weight with flow area is given by the slopes of the curves of figure 4, which are also listed in the following table:

Moderator	Ratio of tungsten weight to void area, W_W/A_V, lb/sq ft		
	600	800	1000
	Slopes of $(W_r)_{min}$, lb/sq ft		
Water	800	1000	1250
Lithium-7 hydride	800	1000	1600
Beryllium	1100	1400	1600
Beryllium oxide	1500	1700	1850

Figure 4(a) indicates increases in $(W_r)_{min}$ of about 1500 pounds per square foot of void area for BeO reactors, 1100 pounds per square foot for Be moderated reactors, and 800 pounds per square foot for Li^7H and H_2O reactors. The corresponding UO_2 investments increased by 178 pounds per square foot of void area in each case for the values of W_W/A_V and $V_{UO_2}/V_{(UO_2+W)}$ used in figure 4(a).

Figure 4(b) shows a similar comparison of $(W_r)_{min}$ for the various moderators at a W_W/A_V of 800 pounds per square foot. The slopes indicate an increase in $(W_r)_{min}$ above 2 square feet of void area of about 1700 pounds per square foot of void area for BeO, 1400 pounds per square foot for Be, and 1000 pounds per square foot for Li^7H and H_2O reactors. For a W_W/A_V of 1000 pounds per square foot figure 4(c) shows an increase in $(W_r)_{min}$ of approximately 1850 pounds per square foot for BeO, 1600 pounds per square foot for Be, and 1250 pounds per square foot for Li^7H and H_2O moderated reactors.

For 1 square foot of reactor void area, which is approximately the requirement for a 1000-megawatt nuclear-rocket reactor, the minimum reactor weights are from figure 4(b) are 4400 pounds for BeO, 2600 pounds for Be, and 1100 pounds for Li^7H and H_2O moderators.

Parametric Study with Water Moderated Reactors

The use of water and Li^7H resulted in lightweight reactors. Water was selected for the parametric study because it seems to have certain design advantages over Li^7H. In particular, the poor thermal and physical properties of Li^7H (ref. 11) indicate major problem areas in the use of this material as a moderator. For this parametric study the value of W_W/A_V was held constant at 800 pounds per square foot. A criticality factor of 1.05 was used instead of a factor of 1 to give a more realistic weight. Any reactor would need a specified amount of excess reactivity to allow for such items as negative temperature coefficients, overriding xenon, and burnup. Values of $V_{UO_2}/V_{(UO_2+W)}$ ranging from 0.30 to 0.10 were used, and the W^{184} concentration was varied parametrically. Since tungsten fully enriched with W^{184} would be difficult to obtain, more readily obtained enrichments, 78 and 58 percent, were assumed. Table II gives the tungsten composition for these enrichments. From the Li^7H results a reactor height of 2 feet consistently resulted in minimum- or near-minimum-weight reactors; therefore, a length of 2 feet was used for the results shown in figure 5.

The effect of tungsten enrichment and void area on the weight of bare, homogeneous H_2O moderated reactors is shown in figure 5(a). The corresponding diameters and uranium investments are shown in figure 5(b).

The reactor weight increases (fig. 5(a)) with decreases in W^{184} percentage. The weight increase at 1 square foot of void area, compared to 100 percent W^{184}, is about 18 and 36 percent for 78 and 58 percent W^{184}, respectively. The weight penalty is less at the larger void areas. For nonhydrogeneous moderators, the weight penalties would be greater because more collisions are needed to slow down neutrons through the resonance-absorption range.

The effect of $V_{UO_2}/V_{(UO_2+W)}$ on reactor weight is shown in figure 6(a). The corresponding reactor diameters and uranium investments are shown in figure 6(b). A tungsten enrichment of 78-percent W^{184} was assumed, and the value of $V_{UO_2}/V_{(UO_2+W)}$ was varied from 0.10 to 0.30.

For a constant $V_{UO_2}/V_{(UO_2+W)}$ of 0.10 in figure 6(a) void areas below approximately 1.5 square feet are unobtainable because of the increased neutron absorption by the water and the reduced amount of UO_2 due to the reduction in void area. The attempt to reduce the void area, therefore, results in a larger reactor (fig. 6(b)) to offset the increased absorption by a decrease in neutron leakage. For a given void area an increase in $V_{UO_2}/V_{(UO_2+W)}$ would be expected to decrease reactor size (fig. 6(b)) and thus reactor weight; this does occur (fig. 6(a)) for values of $V_{UO_2}/V_{(UO_2+W)}$ up to 0.20. For a $V_{UO_2}/V_{(UO_2+W)}$ of 0.30 the increase in uranium weight more than offsets the decrease in moderator weight with reactor size and causes an increase in reactor weight. This reversal is particularly evident at the larger void areas. It is evident from uranium investment (fig. 6(b)) and the curves of reactor weight (fig. 6(a)) that, for void areas larger than 1.5 square feet, a saving in fuel investment can be made by use of low values of $V_{UO_2}/V_{(UO_2+W)}$ (i.e., 0.10 to 0.15) without imposing a penalty in reactor weight.

At void areas below 1.5 square feet, values of $V_{UO_2}/V_{(UO_2+W)}$ in the low range (viz., < 0.10) thus give large increases in reactor weight; above 1.5 square feet, values of $V_{UO_2}/V_{(UO_2+W)}$ in the high range result in high uranium investments. A value of 0.15 to 0.20 appears most suitable to the entire void-area range studied, with a value of 0.10 possible for large void areas if the slight increase in reactor weight is permissible.

SUMMARY OF RESULTS

Weights, sizes, and uranium investments of bare, homogeneous, thermal reactors were determined for a range of reactor void areas. The study considered some of the best moderator materials, beryllium oxide, beryllium, lithium-7 hydride, and water; a fuel-bearing and structural material of high-temperature capability, tungsten highly enriched with tungsten 184; and a highly refractory fuel material, uranium dioxide.

With these materials, criticality calculations for selected values of tungsten and uranium dioxide content as well as a range of void fractions yielded a family of curves of reactor weight as a function of void area for each moderator. An envelope curve, tangent to the curves for constant void fraction, defined the locus of points of minimum reactor weight plotted against void area for each moderator. A comparison of these minimum-reactor-weight curves for the various moderators, as well as a closer study of the effects of tungsten 184 enrichment and the volume ratio of uranium dioxide to uranium dioxide plus tungsten for the water moderated reactors, led to the following results:

1. For 1 square foot of void area (approximately the requirement for a 1000-megawatt nuclear-rocket reactor), a uranium dioxide to uranium dioxide plus tungsten volume ratio of 0.30, 100-percent tungsten 184

enrichment, and 600 pounds of tungsten per square foot of void area, the bare-reactor minimum weights for the various moderators are: 4400 pounds with a beryllium oxide moderator, 2600 pounds with a beryllium moderator, and 1100 pounds with either a lithium-7 hydride or a water moderator.

2. Comparing the minimum-weight reactors over a range of void areas for 600 pounds of tungsten per square foot of void area with 100 percent tungsten 184 and a volume ratio of uranium dioxide to uranium dioxide plus tungsten of 0.30 results in the following: the reactor weight with a beryllium oxide moderator increases approximately 1500 pounds per square foot of void area, the weight with a beryllium moderator increases approximately 1100 pounds per square foot of void area, and the weight with either a lithium hydride or a water moderator increases approximately 800 pounds per square foot of void area.

3. When the amount of tungsten is increased from 600 to 1000 pounds per square foot of void area, the following increases in minimum reactor weights occur: the weight of beryllium oxide moderated reactors increases approximately 25 to 30 percent, the weight of beryllium moderated reactors increases approximately 40 to 50 percent, and the weight of both lithium-7 hydride and water moderated reactors increases 55 to 65 percent.

4. For the water moderated reactors with a uranium dioxide to uranium dioxide plus tungsten volume ratio of 0.15 and a criticality factor of 1.05, the tungsten enrichment with the tungsten 184 isotope was varied from 100 percent tungsten 184 to 58 percent tungsten 184. At 1 square foot of void area the minimum reactor weight increased approximately 18 and 36 percent when the tungsten 184 enrichment was decreased from 100 to 78 percent and from 100 to 58 percent, respectively. For larger void areas this weight penalty is reduced.

5. For the water moderated reactors uranium dioxide to uranium dioxide plus tungsten the volume ratio was varied from 0.30 to 0.10. At void areas below 1.5 square feet, values of the volume ratio of uranium dioxide to uranium dioxide plus tungsten between 0.10 and 0.15 may result in large increases in reactor weight. Above 1.5 square feet, the higher values of the volume ratio of uranium dioxide to uranium dioxide plus tungsten result in increased uranium investments. A value of the uranium dioxide to uranium dioxide plus tungsten volume ratio of 0.15 to 0.20 appeared most suitable for the void range studied, with a value of 0.10 possible for higher void areas.

Lewis Research Center
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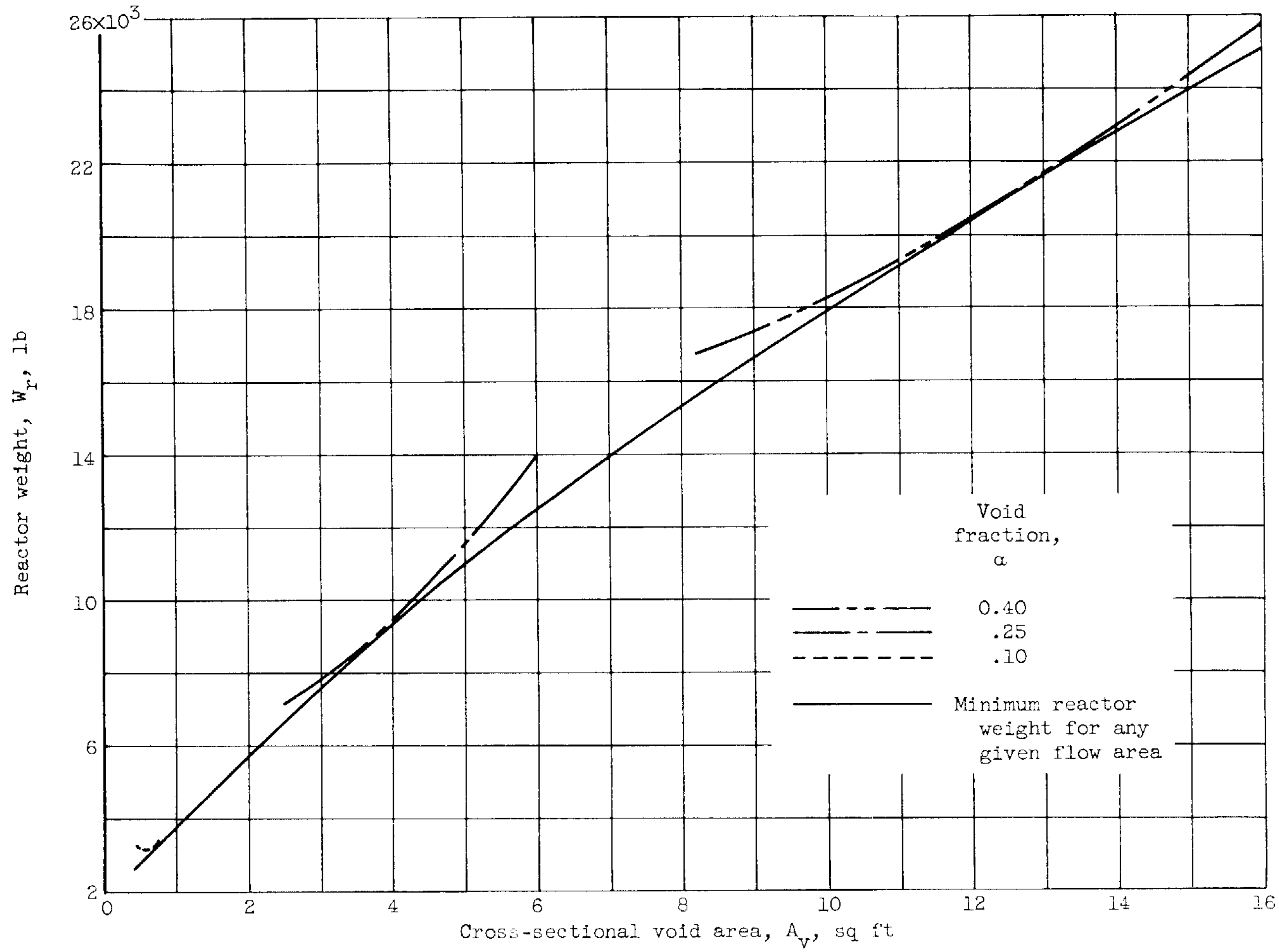
TABLE I. - MATERIAL DENSITIES

Material	Atomic or molecular density
Beryllium	0.1236×10^{24}
Beryllium oxide	.0728
Water	.0335
Lithium-7 hydride	.0621
Tungsten	.0632
Uranium dioxide	.0223

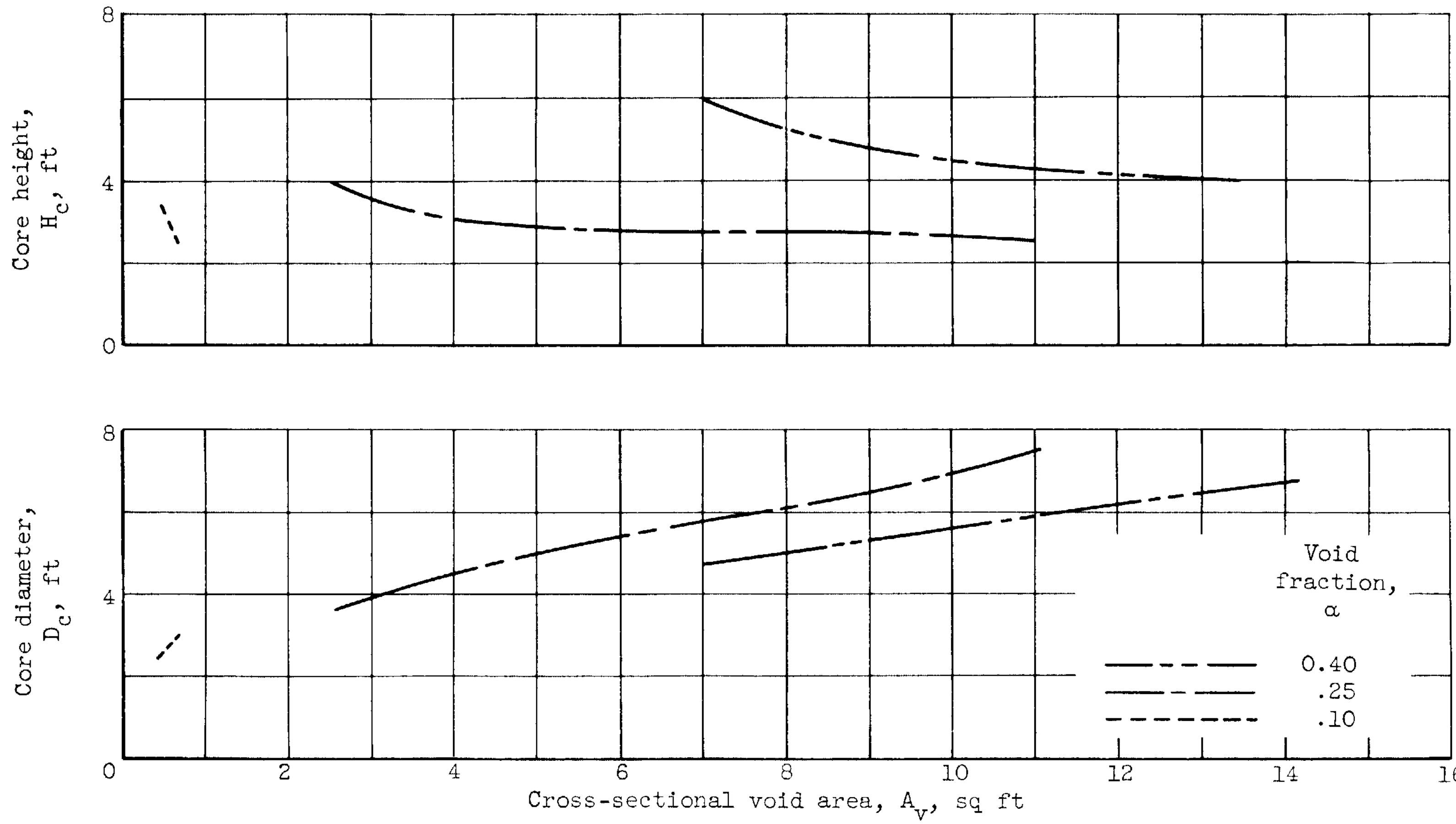
TABLE II. - ISOTOPIC MIXTURES FOR ENRICHED TUNGSTEN 184

Isotope	Tungsten 184, percent			Natural tungsten
	100	78	58	
Tungsten 182	0	3.4	13.9	26.4
Tungsten 183	0	17.1	27.6	14.4
Tungsten 184	100	78.4	57.9	30.6
Tungsten 186	0	1.1	.6	28.4



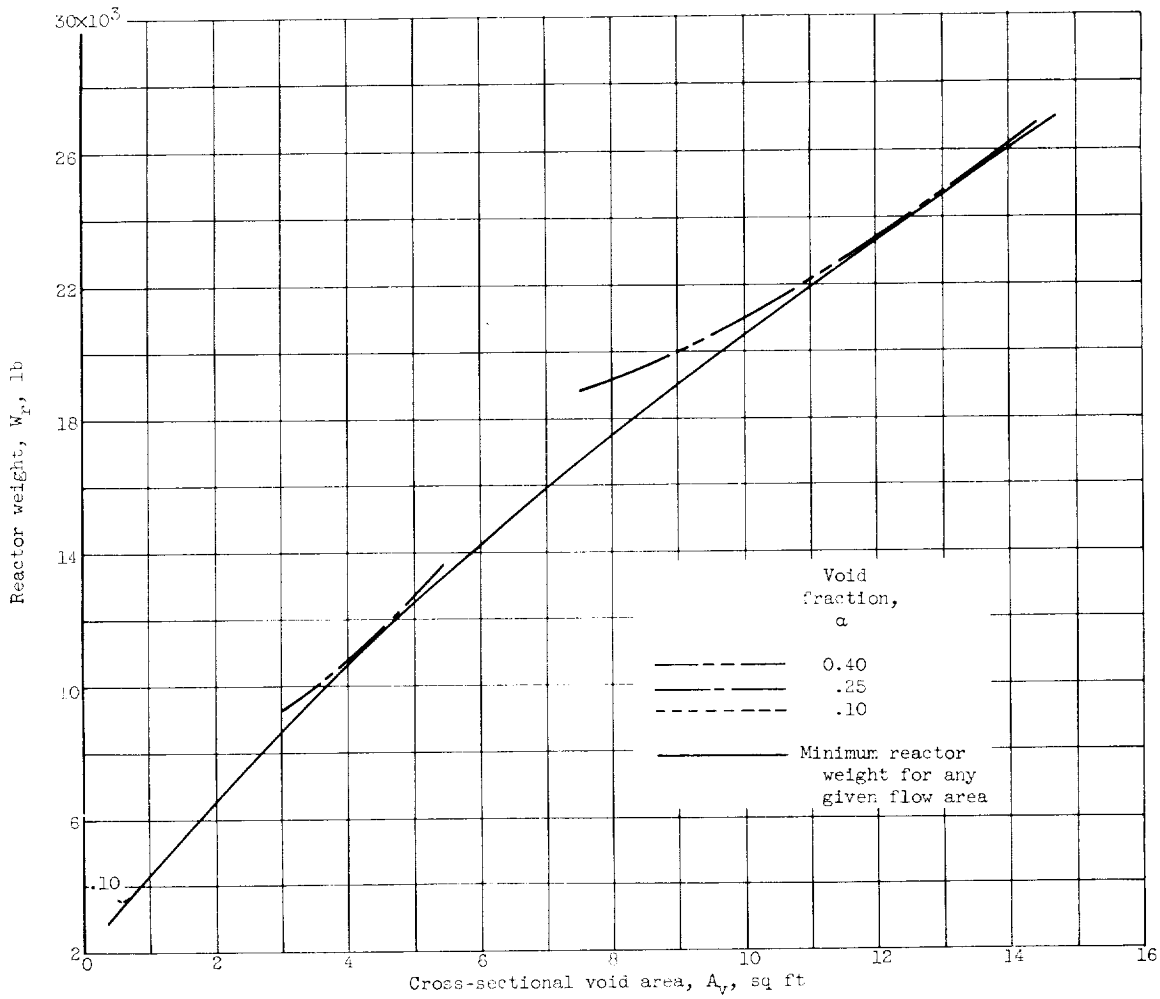
(a) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 600 pounds.

Figure 1. - Weights and dimensions of bare, homogeneous beryllium oxide moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



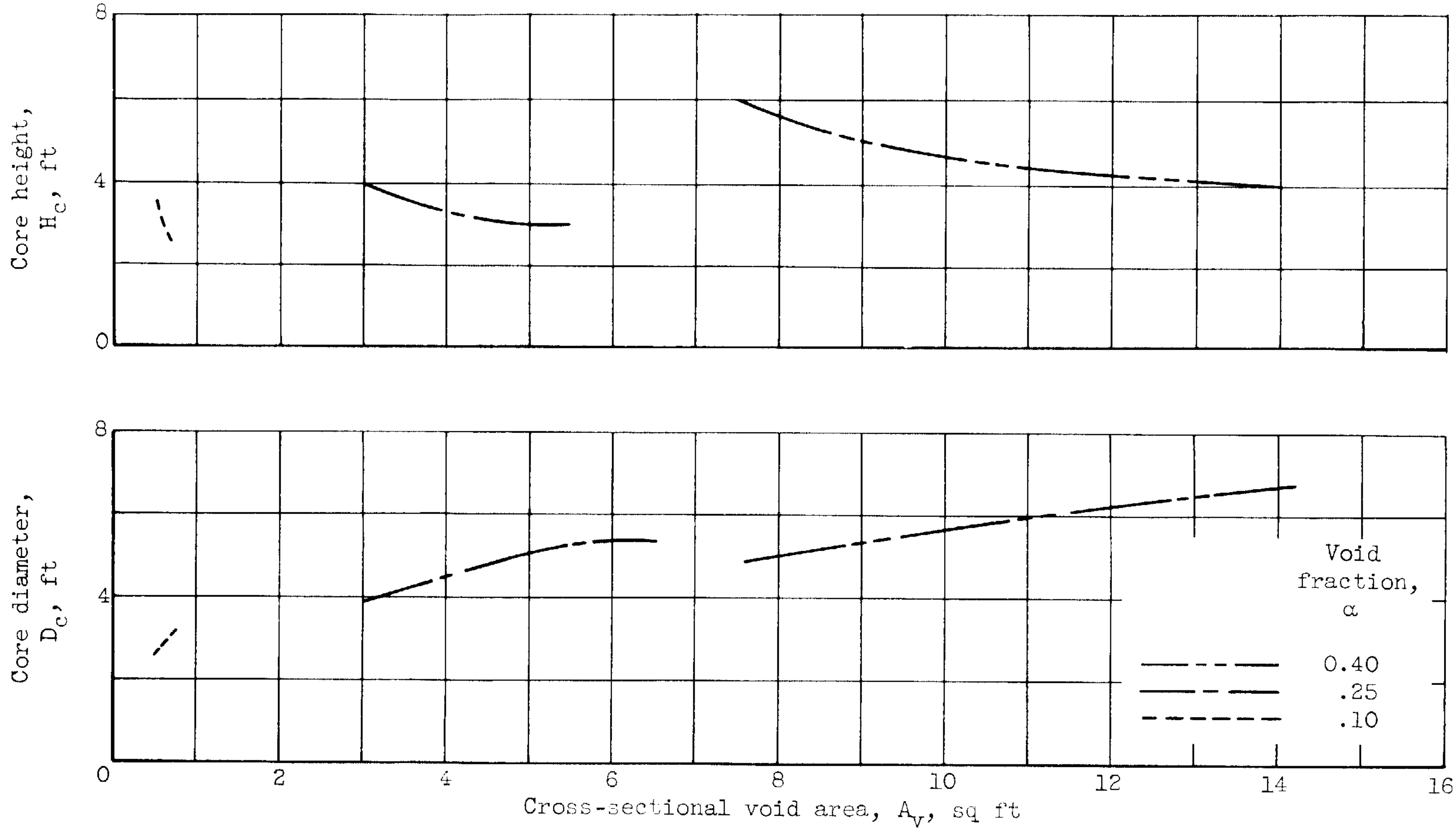
(b) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 600 pounds.

Figure 1. - Continued. Weights and dimensions of bare, homogeneous beryllium oxide moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



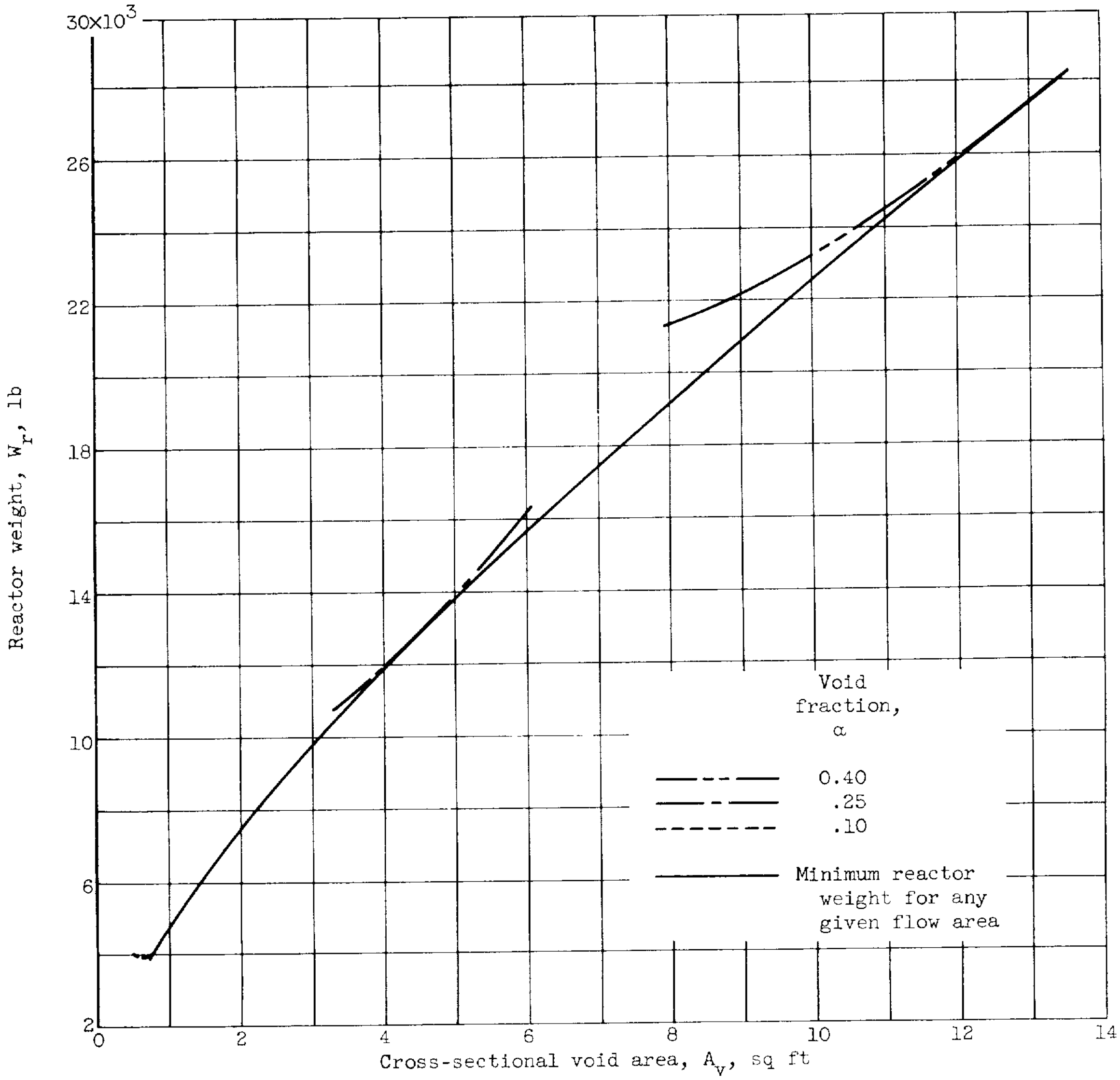
(c) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 800 pounds.

Figure 1. - Continued. Weights and dimensions of bare, homogeneous beryllium oxide moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



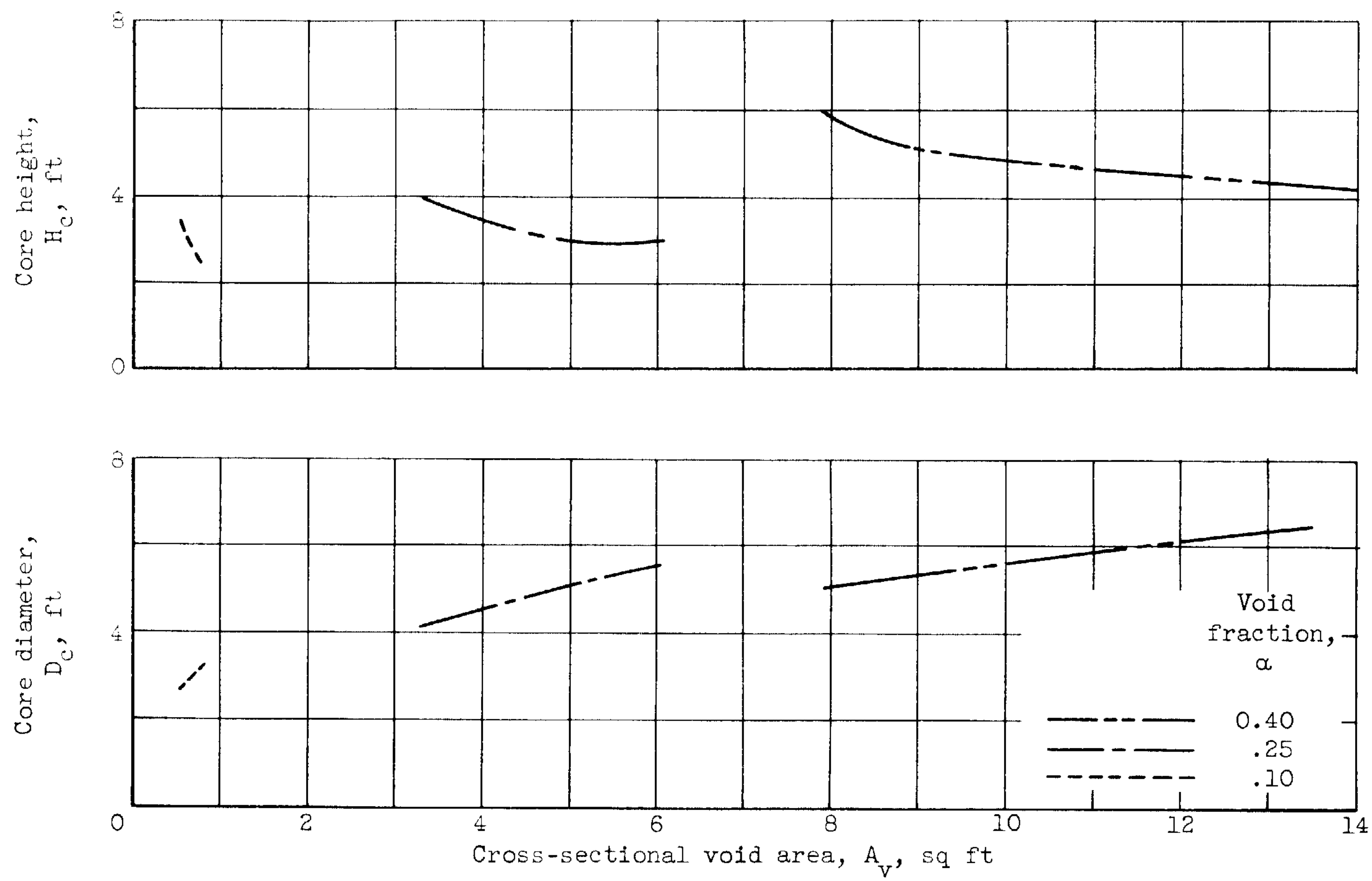
(d) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 800 pounds.

Figure 1. - Continued. Weights and dimensions of bare, homogeneous beryllium oxide moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



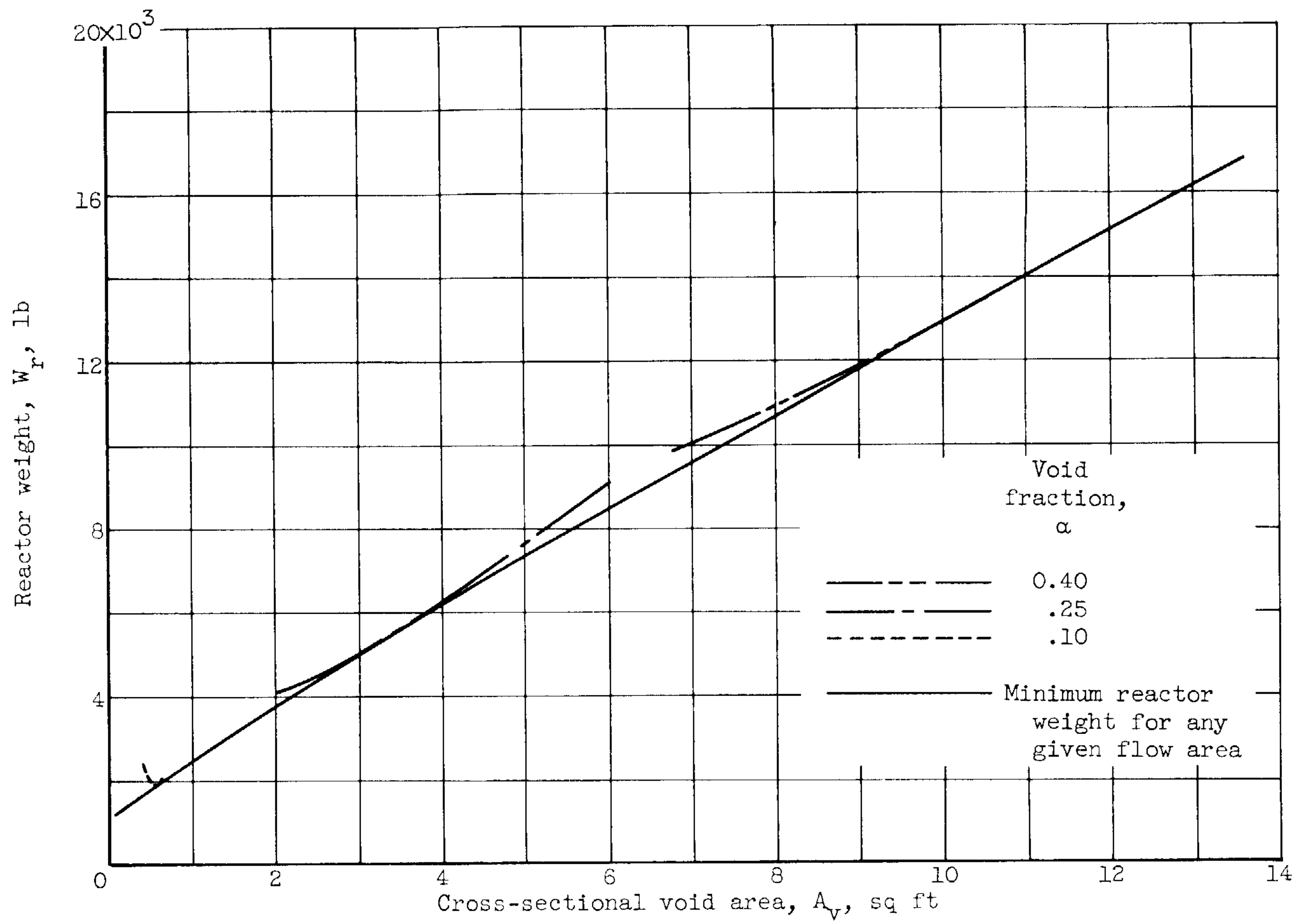
(e) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 1000 pounds.

Figure 1. - Continued. Weights and dimensions of bare, homogeneous beryllium oxide moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality uranium dioxide factor, 1.



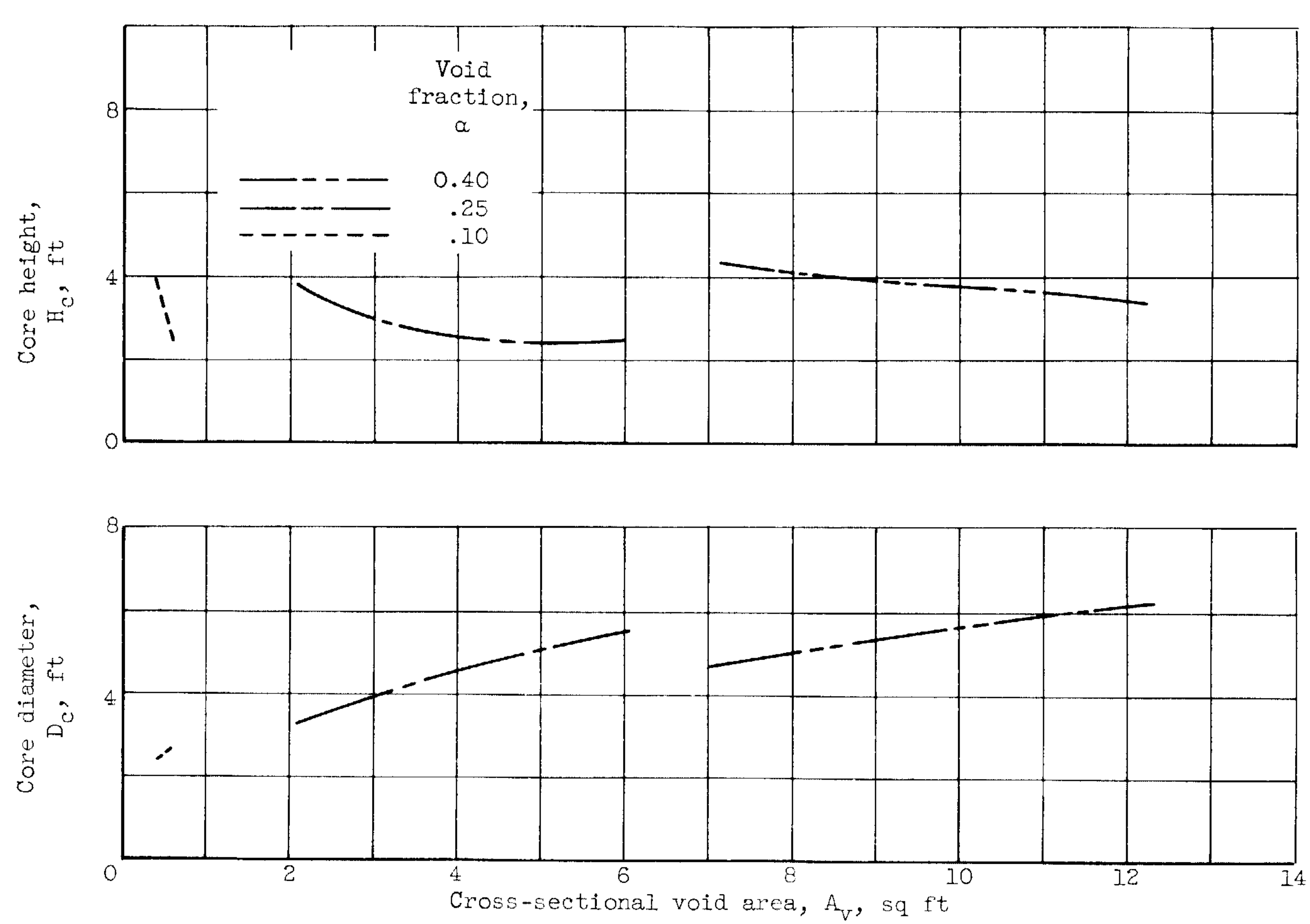
(f) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 1000 pounds.

Figure 1. - Concluded. Weights and dimensions of bare, homogeneous beryllium oxide moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



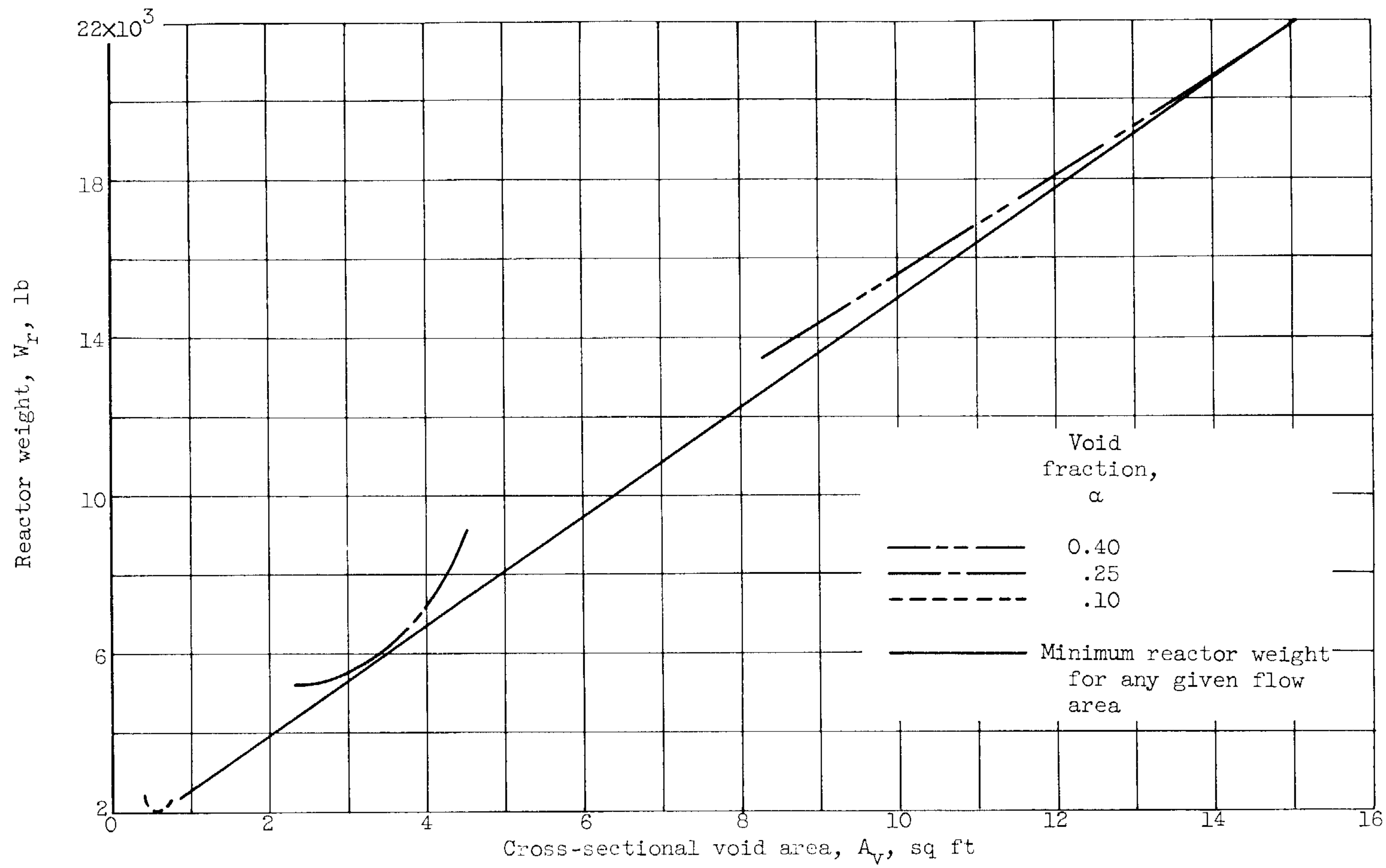
(a) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 600 pounds.

Figure 2. - Weights and dimensions of bare, homogeneous beryllium moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



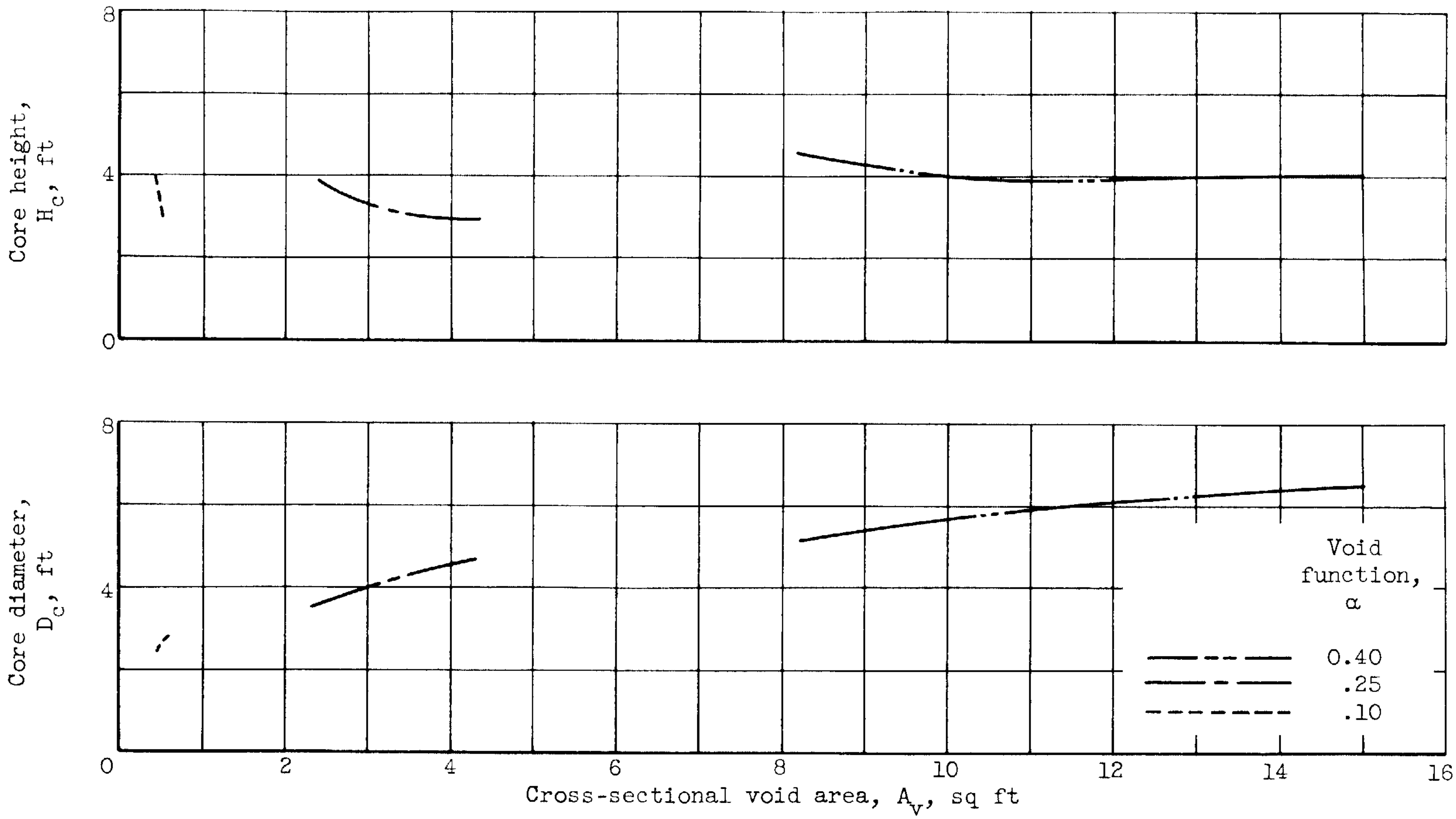
(b) Reactor dimensions. Weight of tungsten per square foot cross-sectional void area, 600 pounds.

Figure 2. - Continued. Weights and dimensions of bare, homogeneous beryllium moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



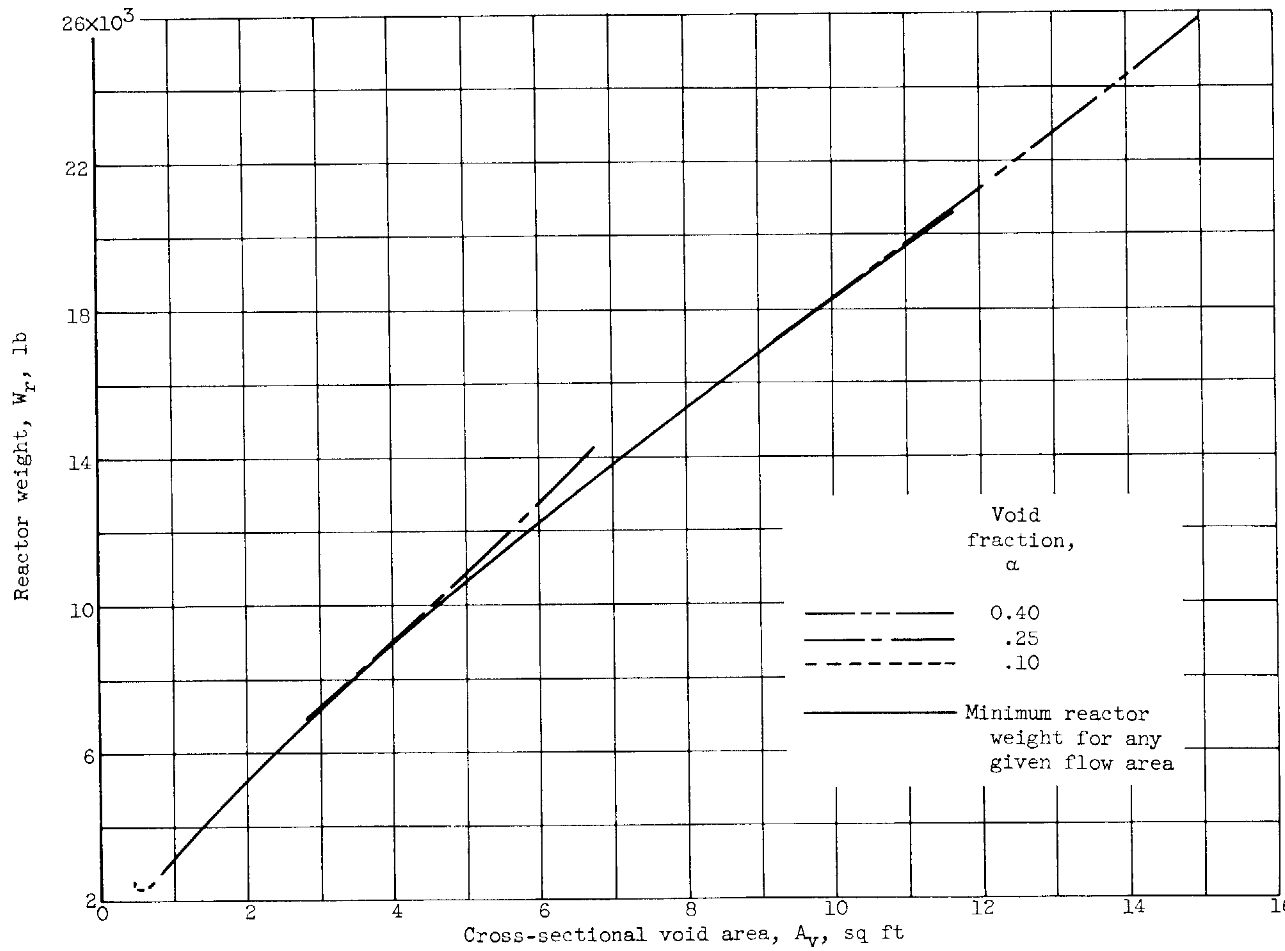
(c) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 800 pounds.

Figure 2. - Continued. Weights and dimensions of bare, homogeneous beryllium moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



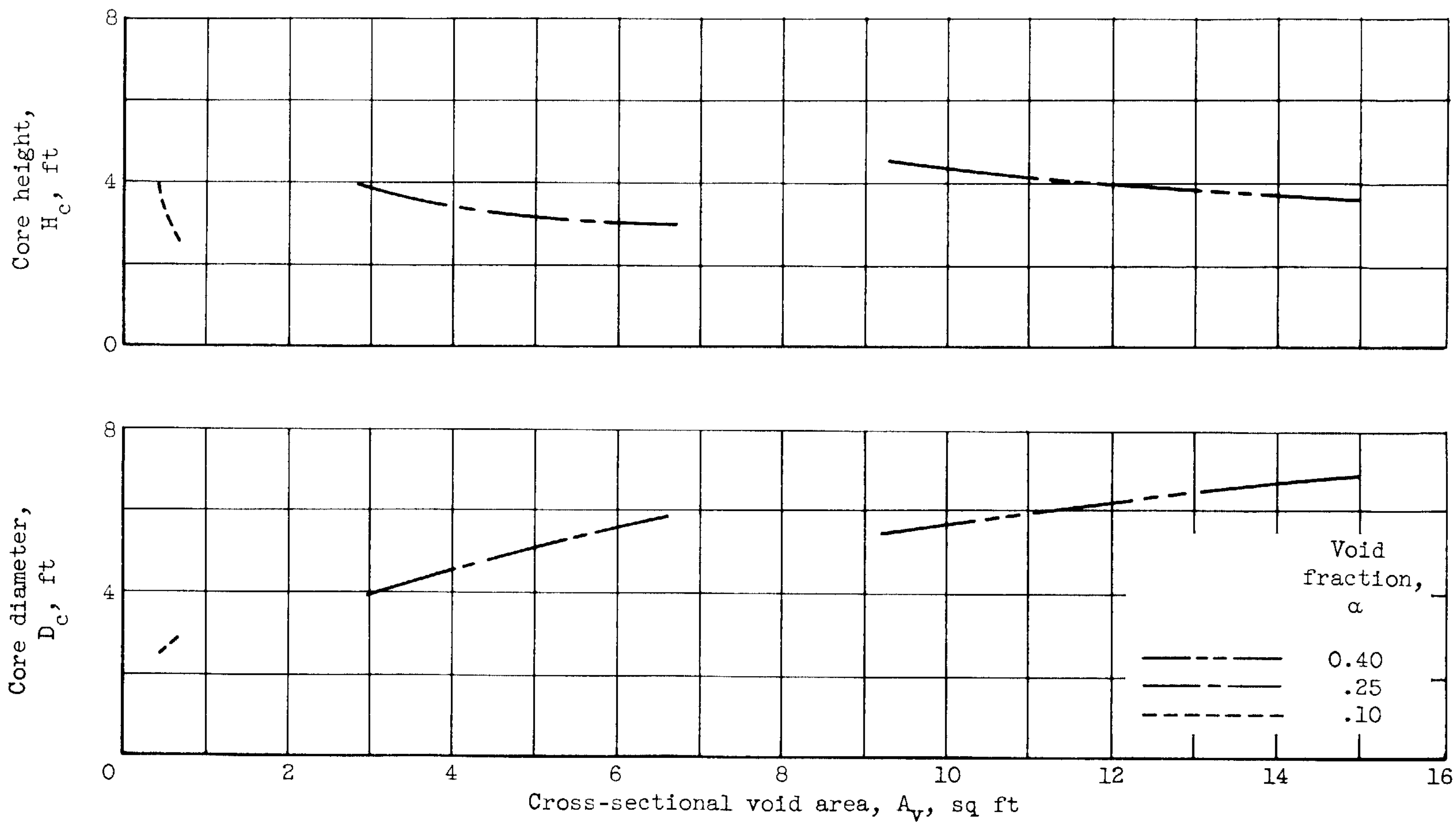
(d) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 800 pounds.

Figure 2. - Continued. Weights and dimensions of bare, homogeneous beryllium moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



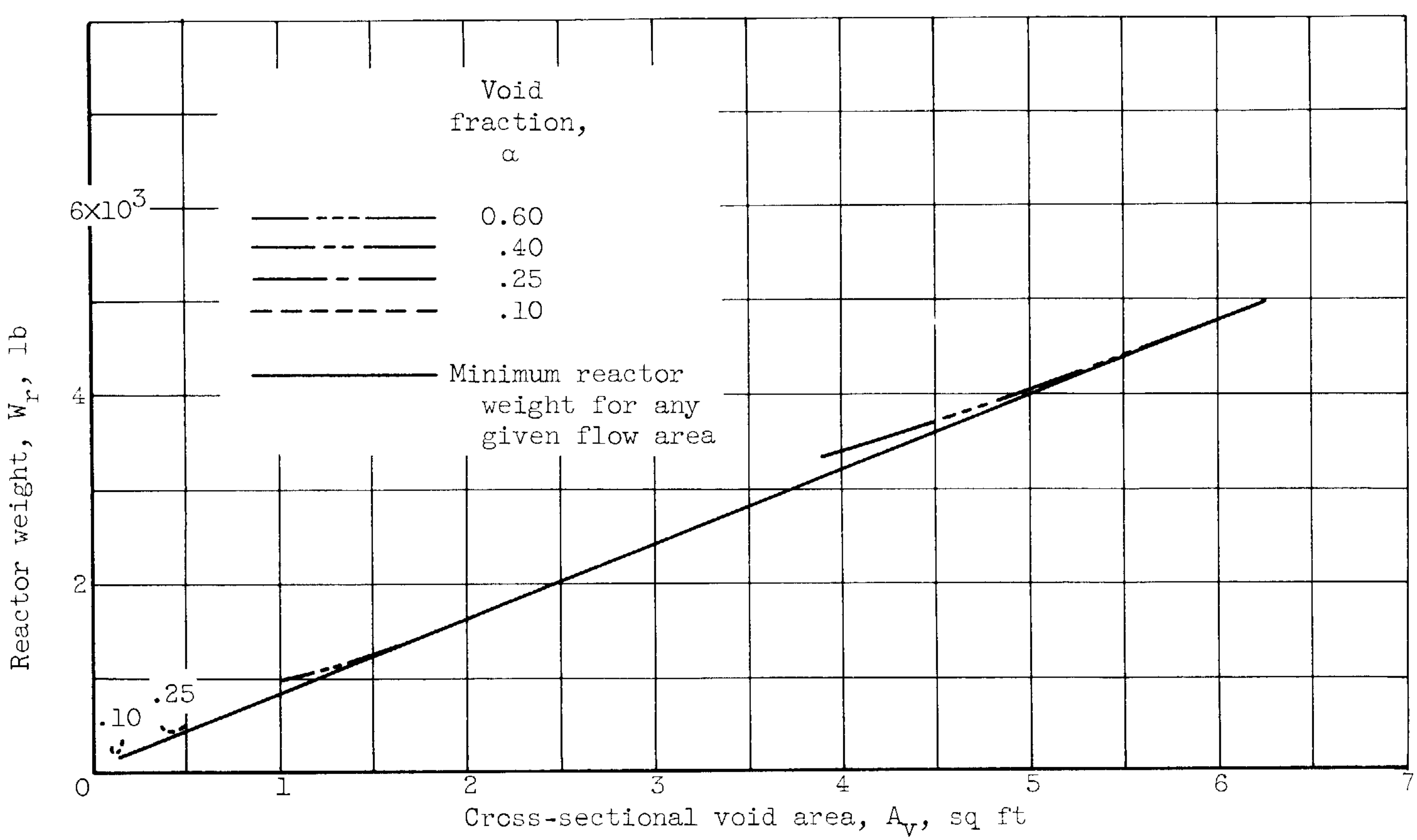
(e) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 1000 pounds.

Figure 2. - Continued. Weights and dimensions of bare, homogeneous beryllium moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



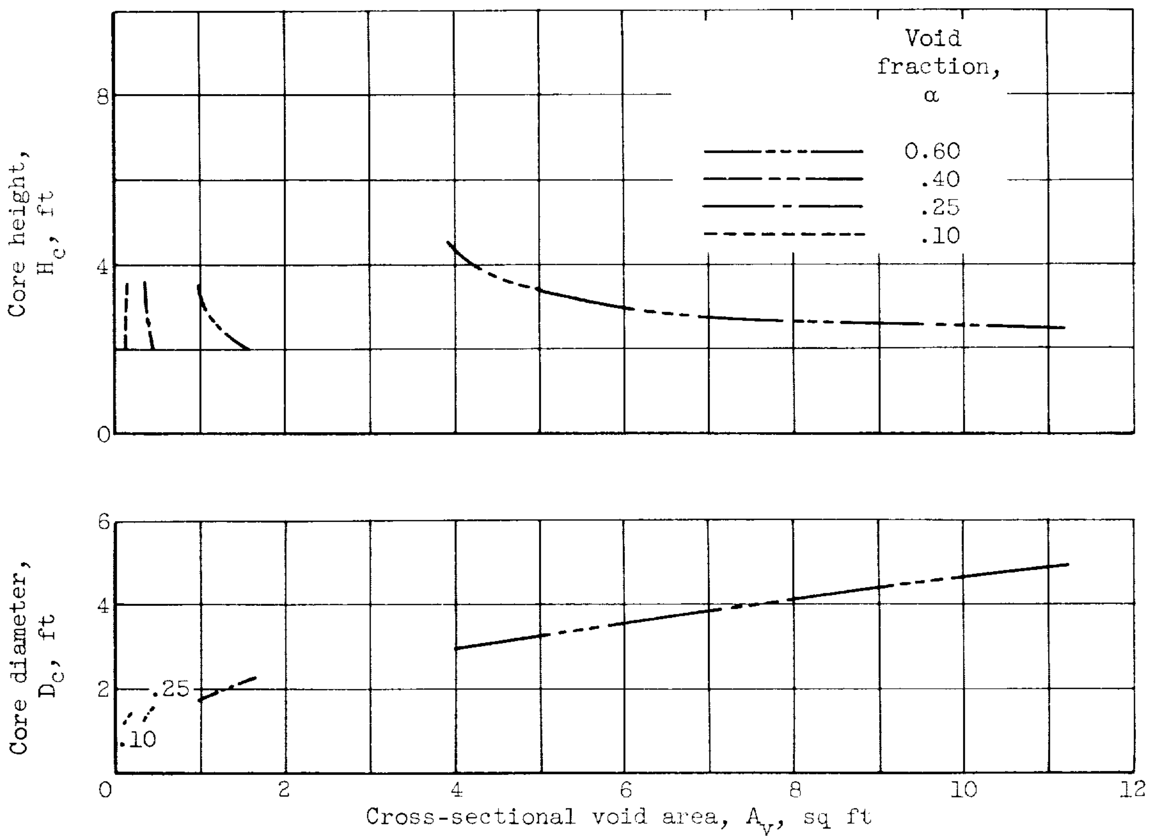
(f) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 1000 pounds.

Figure 2. - Concluded. Weights and dimensions of bare, homogeneous beryllium moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



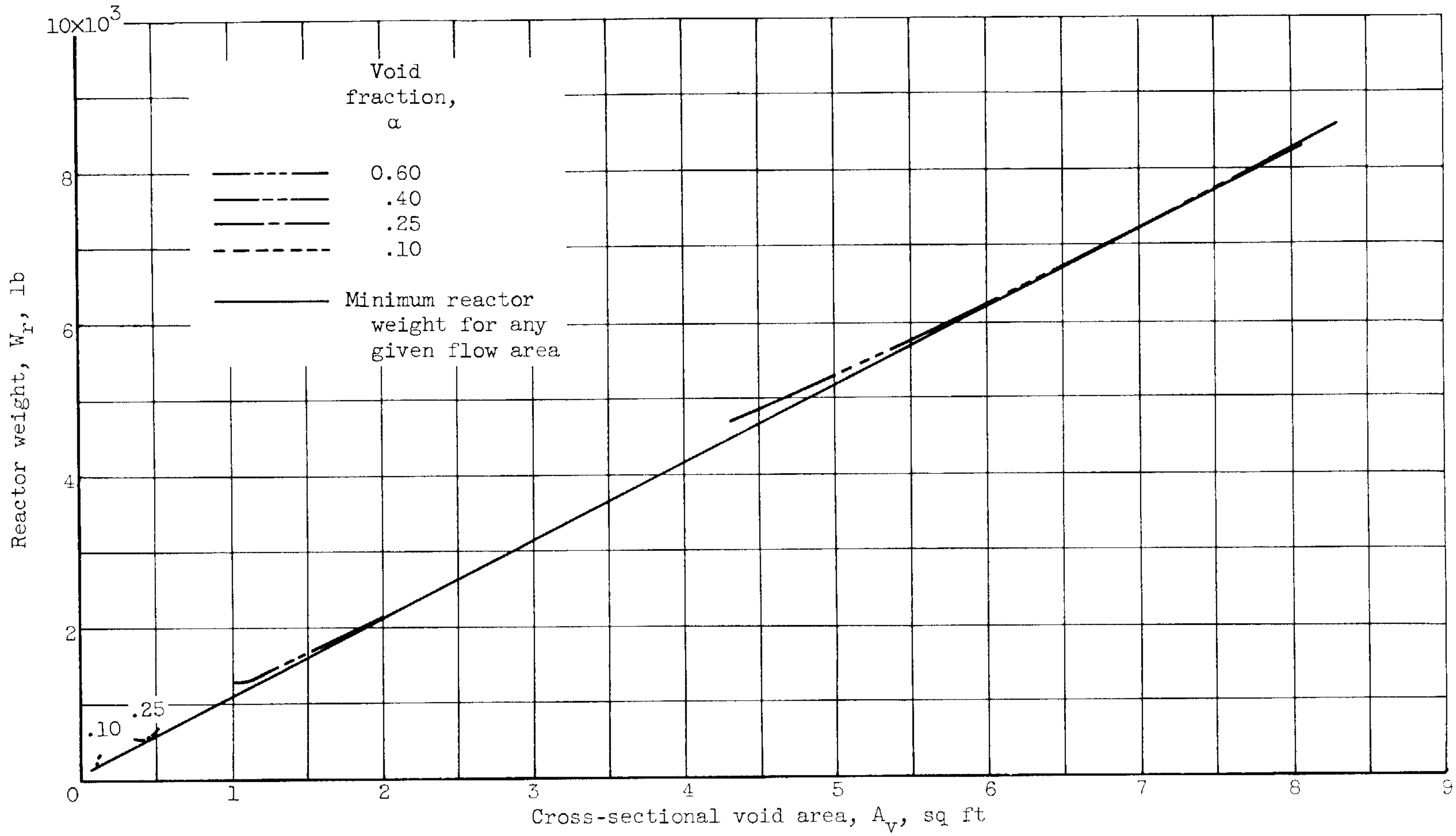
(a) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 600 pounds.

Figure 3. - Weights and dimensions of bare, homogeneous lithium-7 hydride moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



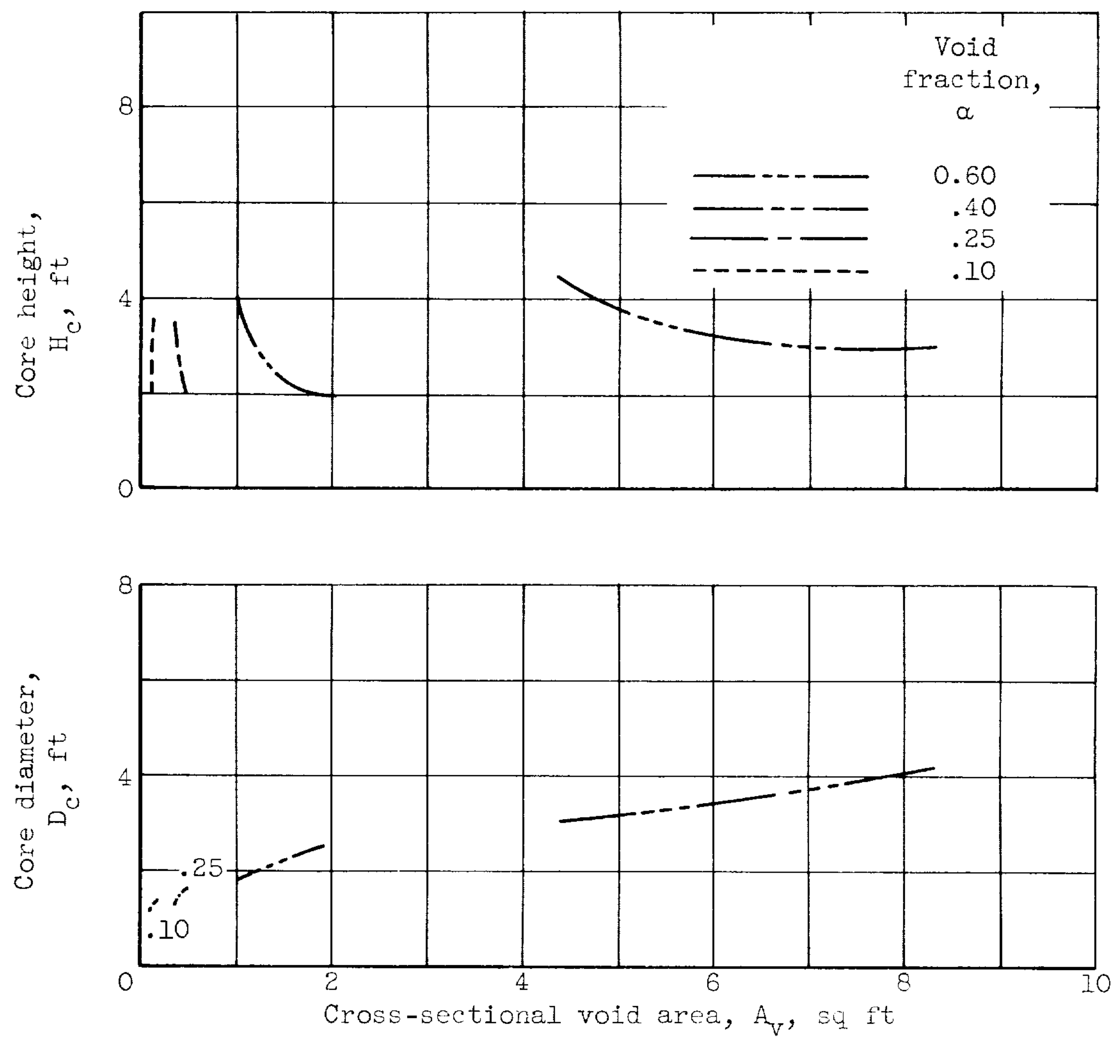
(b) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 600 pounds.

Figure 3. - Continued. Weights and dimensions of bare, homogeneous lithium-7 hydride moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



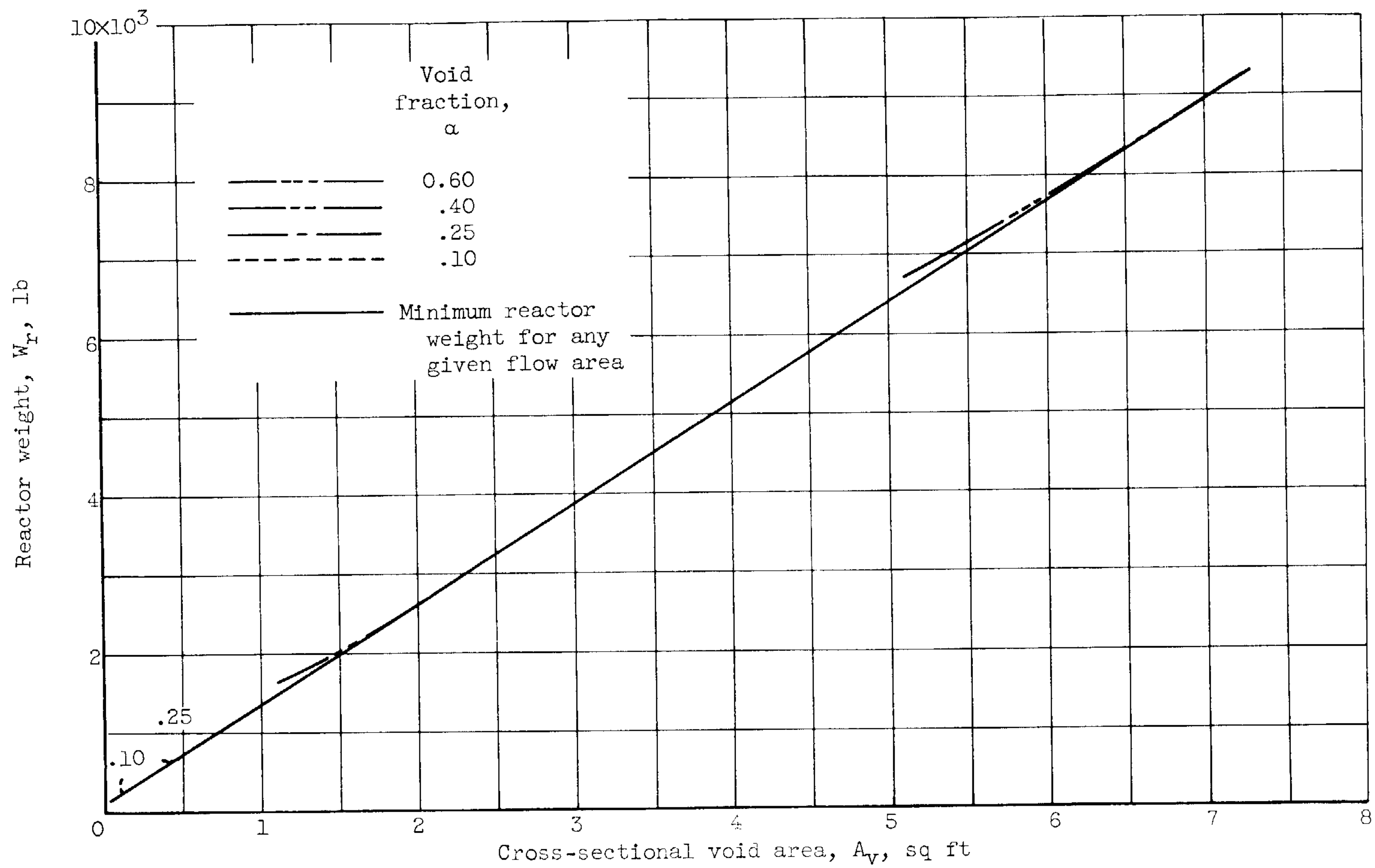
(c) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 800 pounds.

Figure 3. - Continued. Weights and dimensions of bare, homogeneous lithium-7 hydride moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



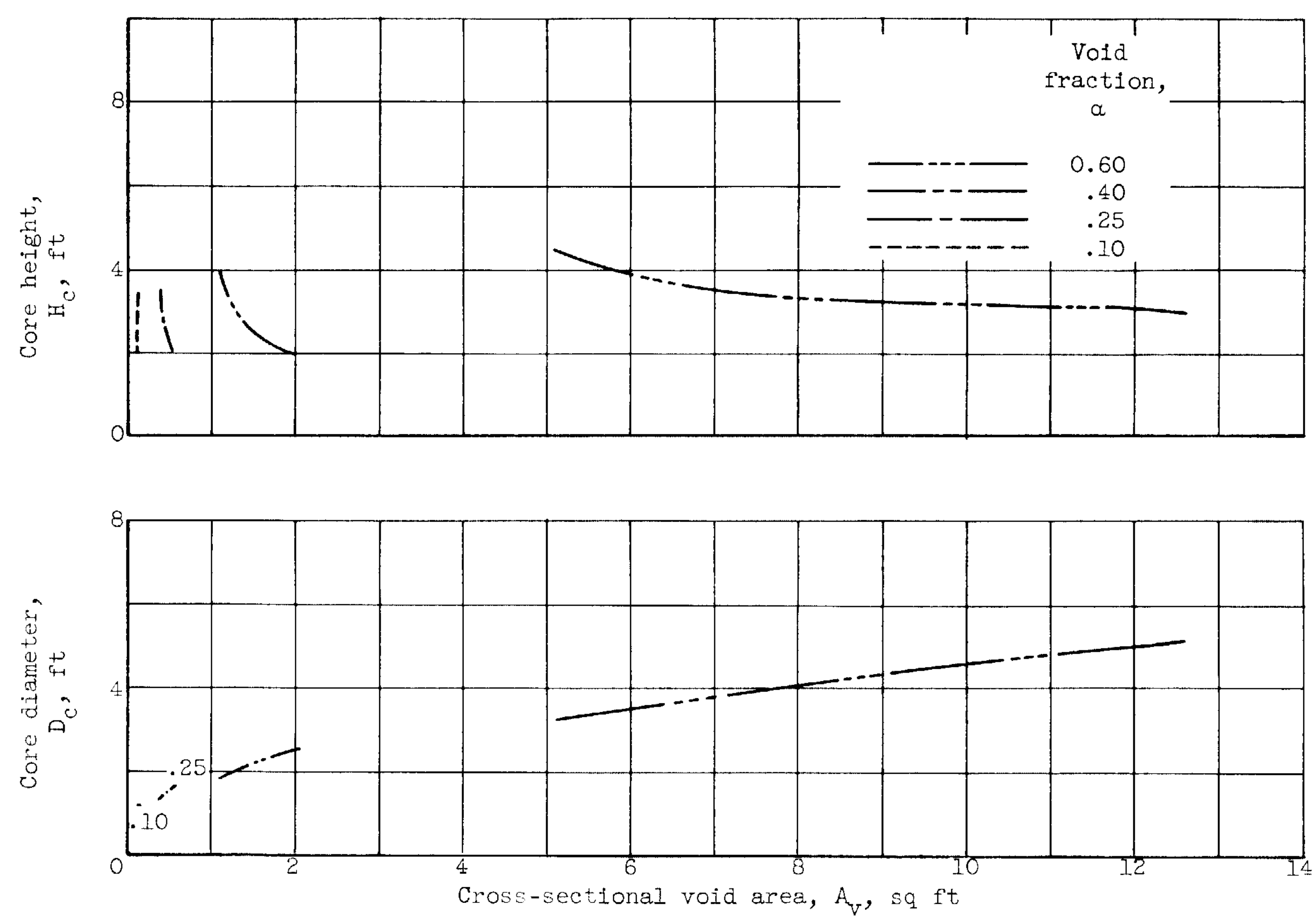
(d) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 800 pounds.

Figure 3. - Continued. Weights and dimensions of bare, homogeneous lithium-7 hydride moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



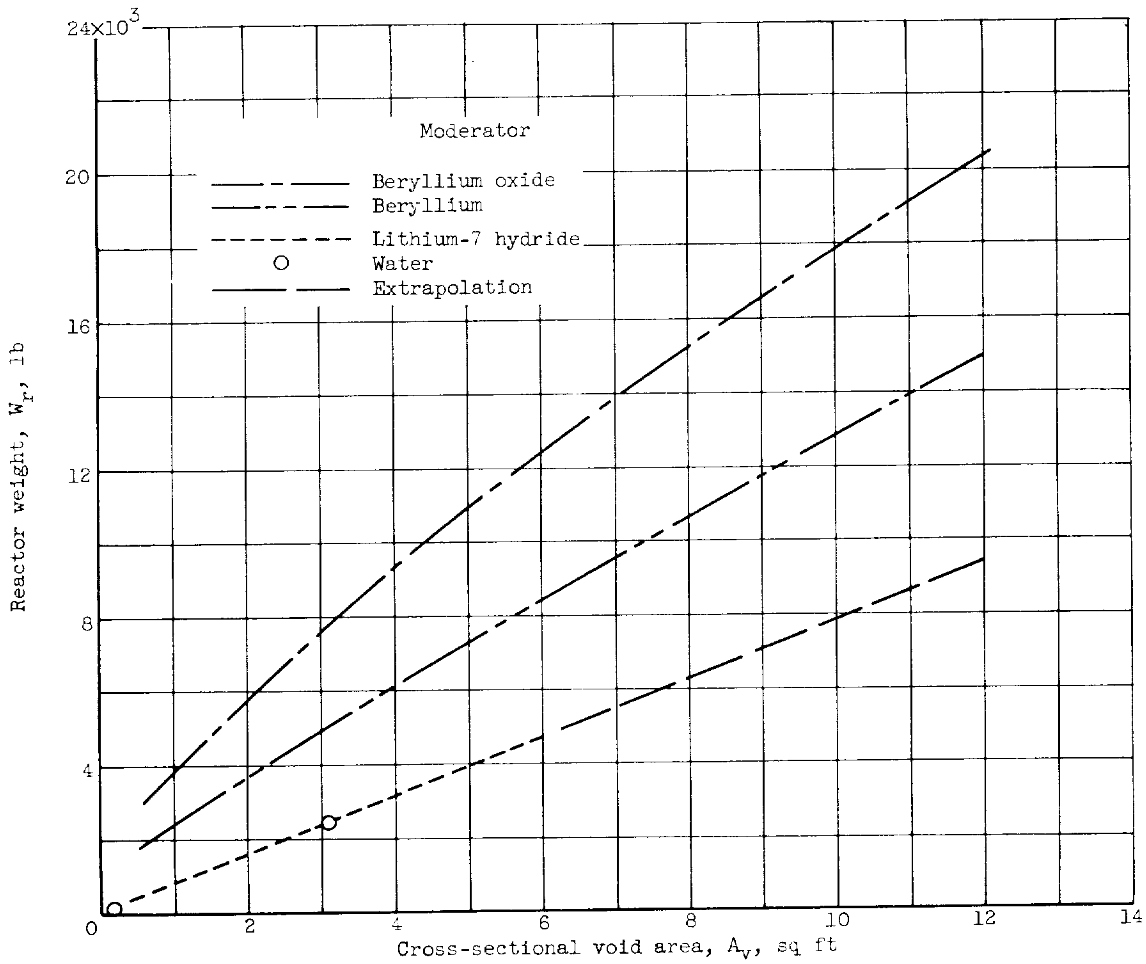
(e) Minimum-reactor-weight curves. Weight of tungsten per square foot of cross-sectional void area, 1000 pounds.

Figure 3. - Continued. Weights and dimensions of bare, homogeneous lithium-7 hydride moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten-184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



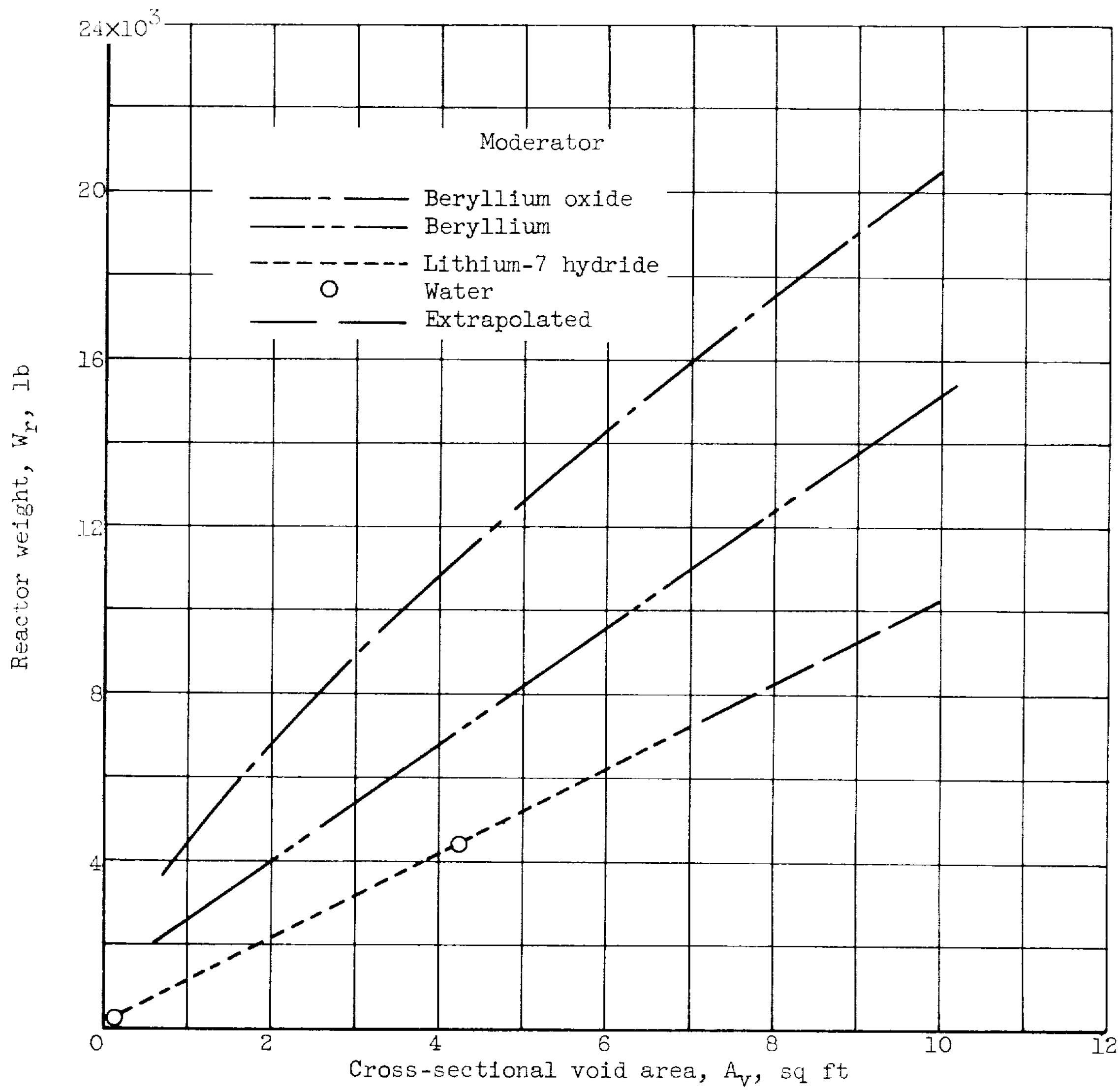
(f) Reactor dimensions. Weight of tungsten per square foot of cross-sectional void area, 1000 pounds.

Figure 3. - Concluded. Weights and dimensions of bare, homogeneous lithium-7 hydride moderated reactors as functions of reactor cross-sectional area and void fraction. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



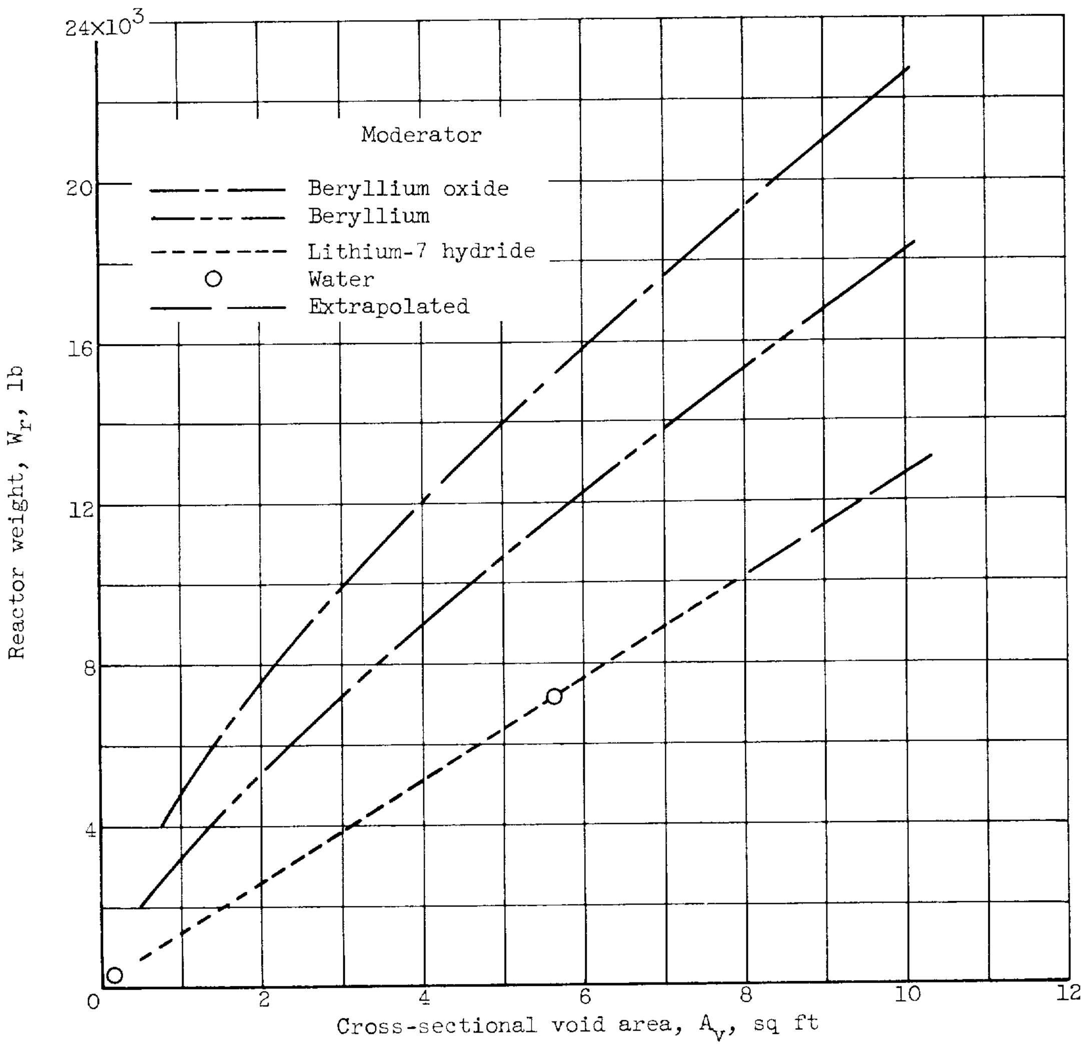
(a) Weight of tungsten per square foot of cross-sectional void area, 600 pounds.

Figure 4. - Minimum-reactor-weight envelope curves for bare, homogeneous reactors with various moderators. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



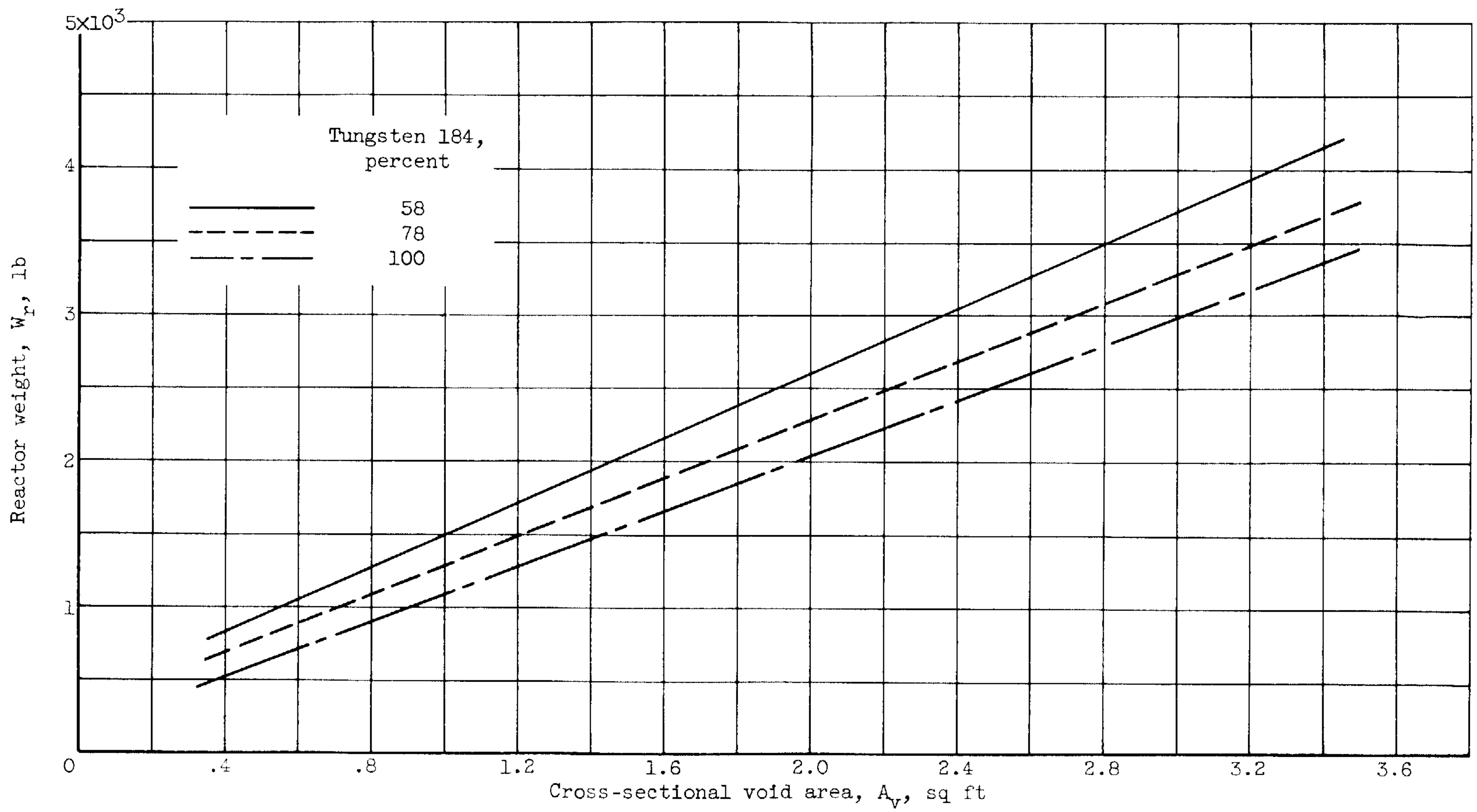
(b) Weight of tungsten per square foot of cross-sectional void area, 800 pounds.

Figure 4. - Continued. Minimum-reactor-weight envelope curves for bare, homogeneous reactors with various moderators. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



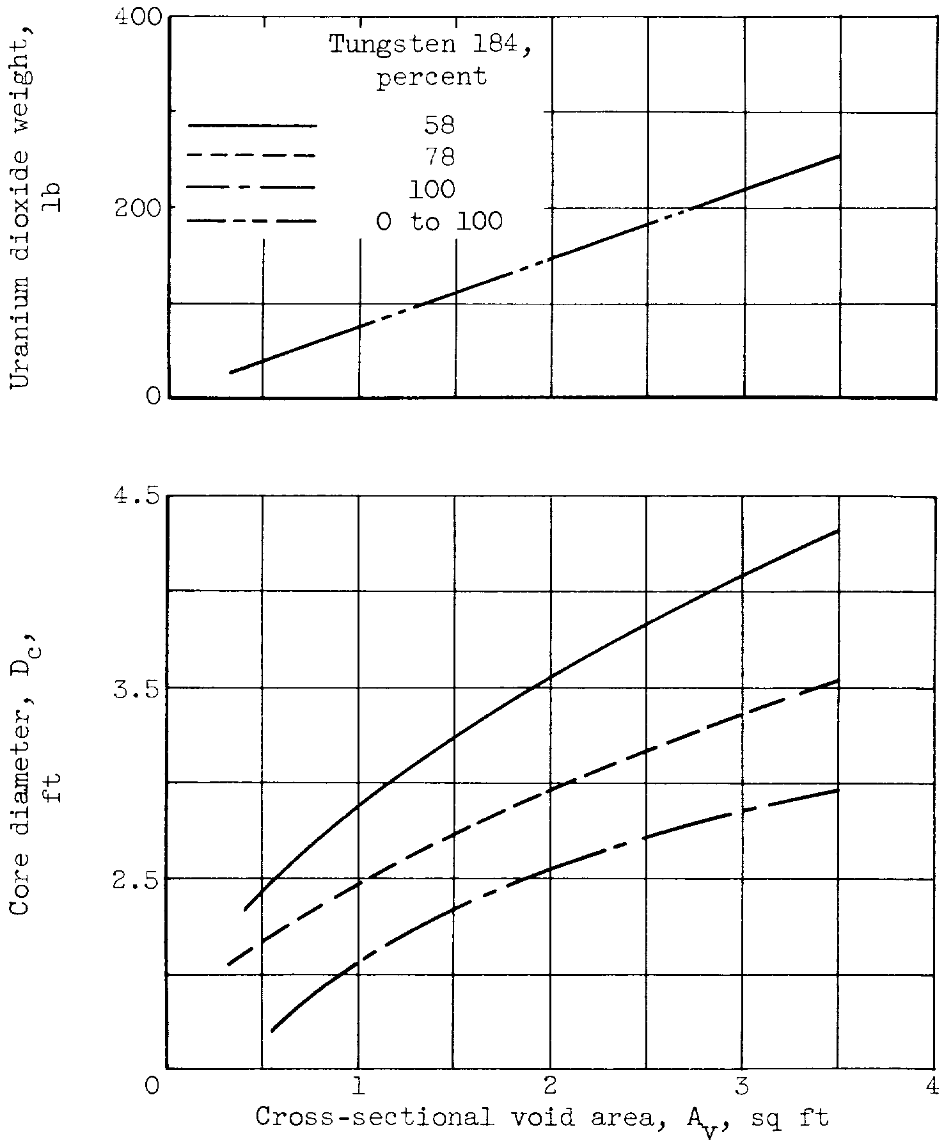
(c) Weight of tungsten per square foot of cross-sectional void area, 1000 pounds.

Figure 4. - Concluded. Minimum-reactor-weight envelope curves for bare, homogeneous reactors with various moderators. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.30; enrichments: tungsten 184, 100 percent, and uranium 235, 93 percent; static criticality factor, 1.



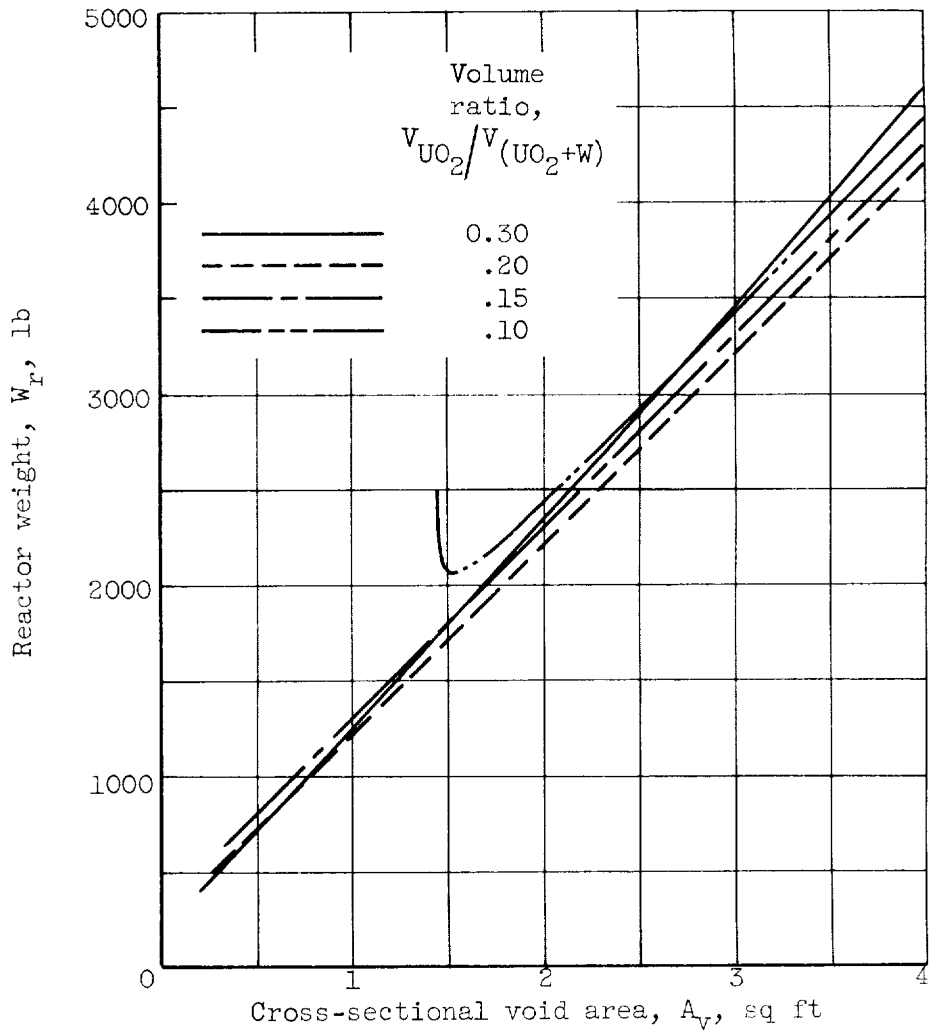
(a) Minimum reactor weight.

Figure 5. - Effect of tungsten 184 enrichment on bare, homogeneous water moderated reactor. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.15; weight of tungsten per square foot of cross-sectional void area, 800 pounds; reactor height, 2 feet.



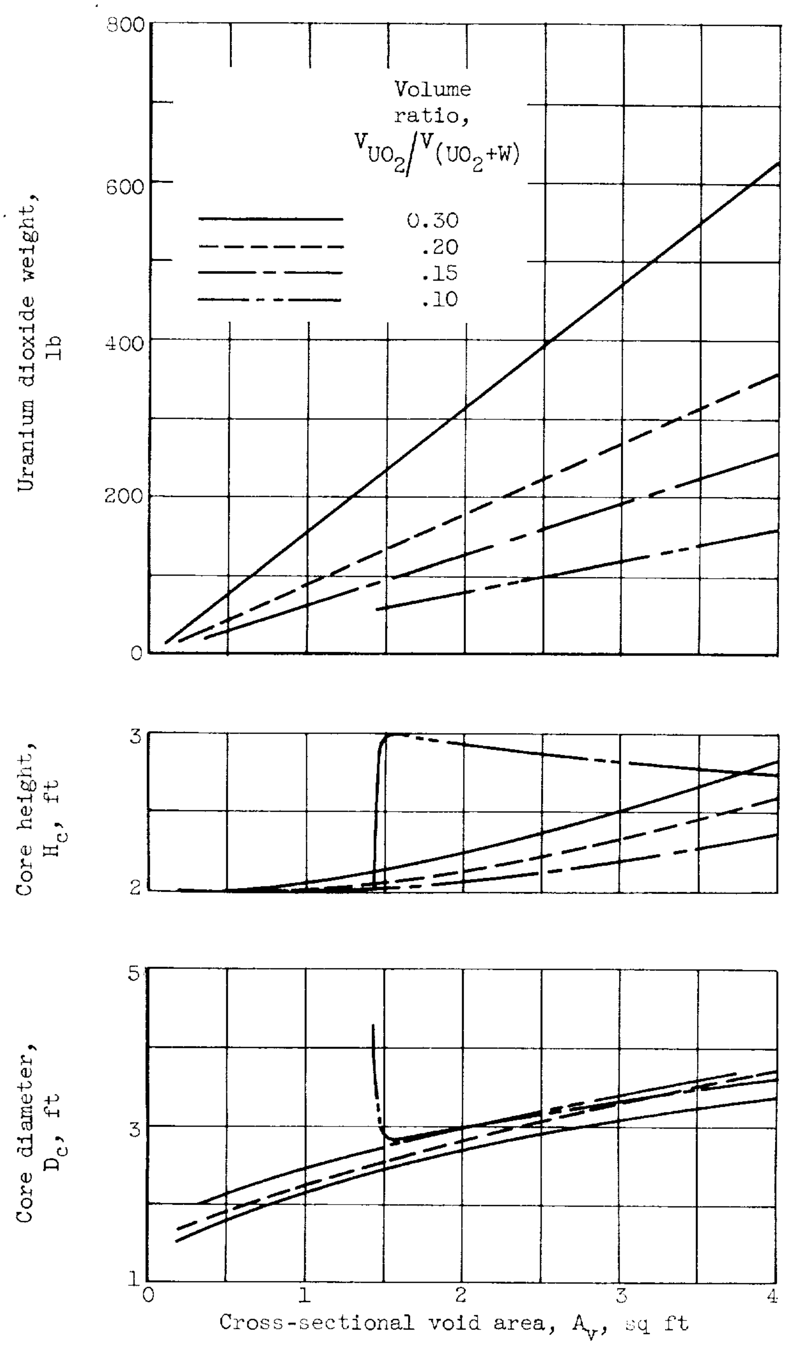
(b) Reactor diameters and uranium dioxide investments.

Figure 5. - Concluded. Effect of tungsten 184 enrichment on bare, homogeneous water moderated reactor. Volume ratio of uranium dioxide to uranium dioxide plus tungsten, 0.15; weight of tungsten per square foot of cross-sectional void area, 800 pounds; reactor height, 2 feet.



(a) Minimum reactor weight.

Figure 6. - Effect of volume ratio of uranium dioxide to uranium dioxide plus tungsten on bare, homogeneous water moderated reactor. Enrichments: tungsten 184, 78 percent, and uranium 235, 93 percent; weight of tungsten per square foot of cross-sectional void area, 800 pounds; static criticality factor, 1.05.



(b) Reactor dimensions and uranium dioxide investment.

Figure 6. - Concluded. Effect of volume ratio of uranium dioxide to uranium dioxide plus tungsten on bare, homogeneous water moderated reactor. Enrichments: tungsten 184, 78 percent, and uranium 235, 93 percent; weight of tungsten per square foot of cross-sectional void are, 800 pounds; static criticality factor, 1.05.